Experimental and theoretical studies of Sn droplet shaping by picosecond laser pre-pulses

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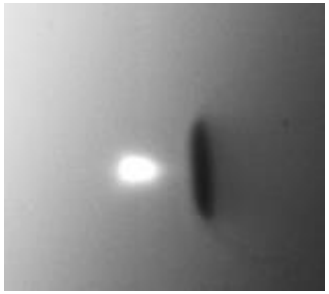
[1] RnD-ISAN/EUV Labs, Moscow, Troitsk, Russia

[2] Institute for Spectroscopy RAS, Moscow, Troitsk, Russia

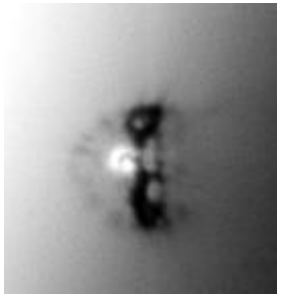
[3] Keldysh Institute of Applied Mathematics RAS, Moscow, Russia

Why picosecond pre-pulse?

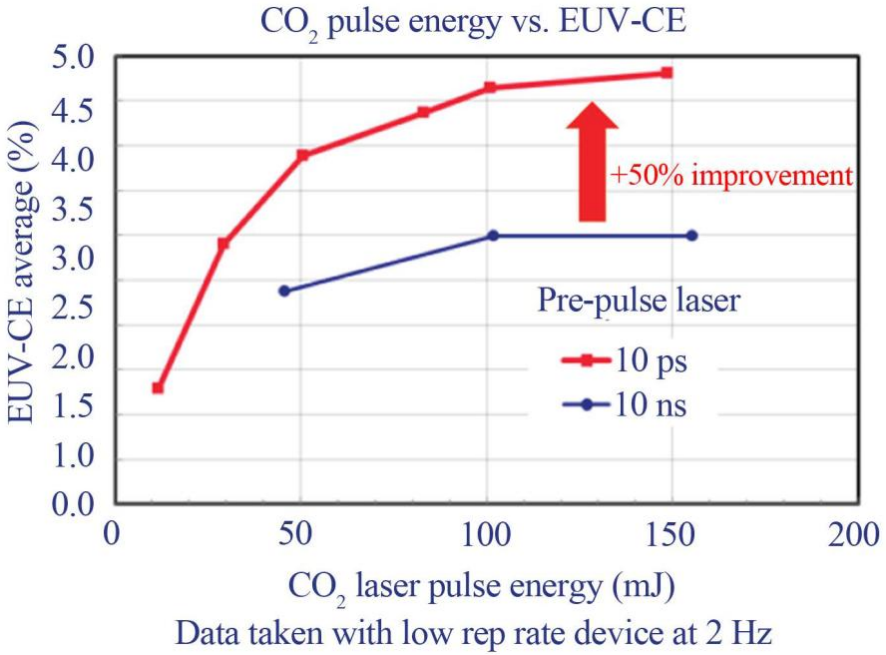
~ 10 ns pre-pulse
"Disk like target"



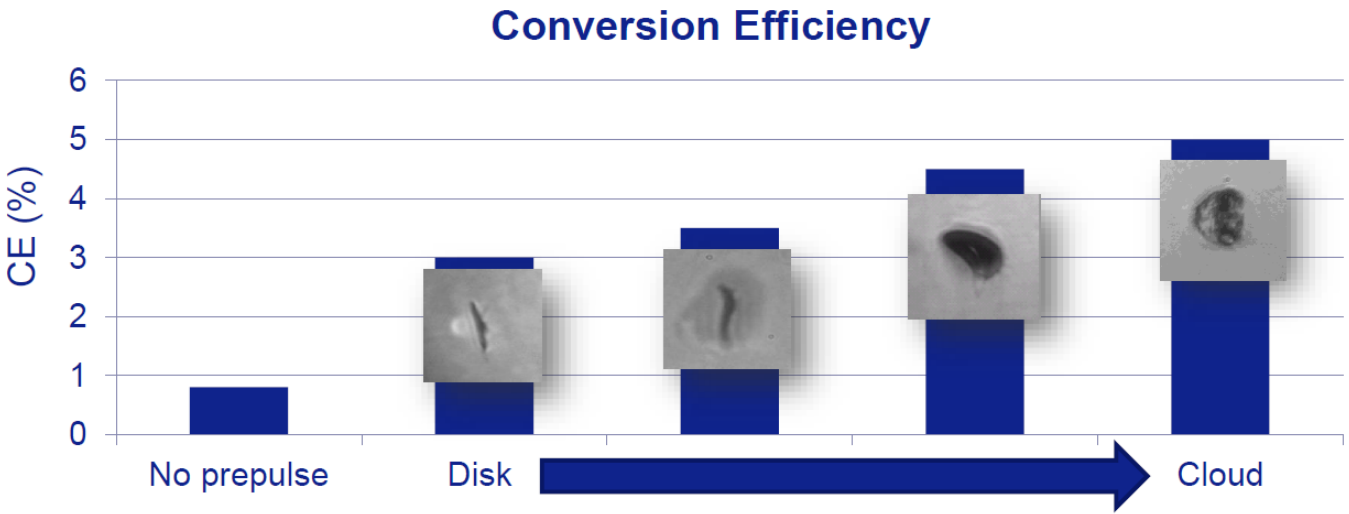
~ 10 ps pre-pulse
"Dome like target"



H. Mizoguchi, EUV Source Workshop, Dublin (2013)



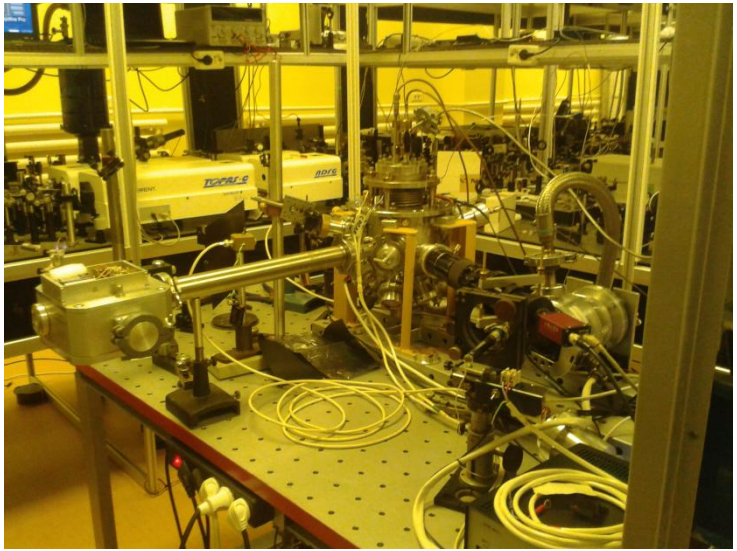
Why picosecond pre-pulse?

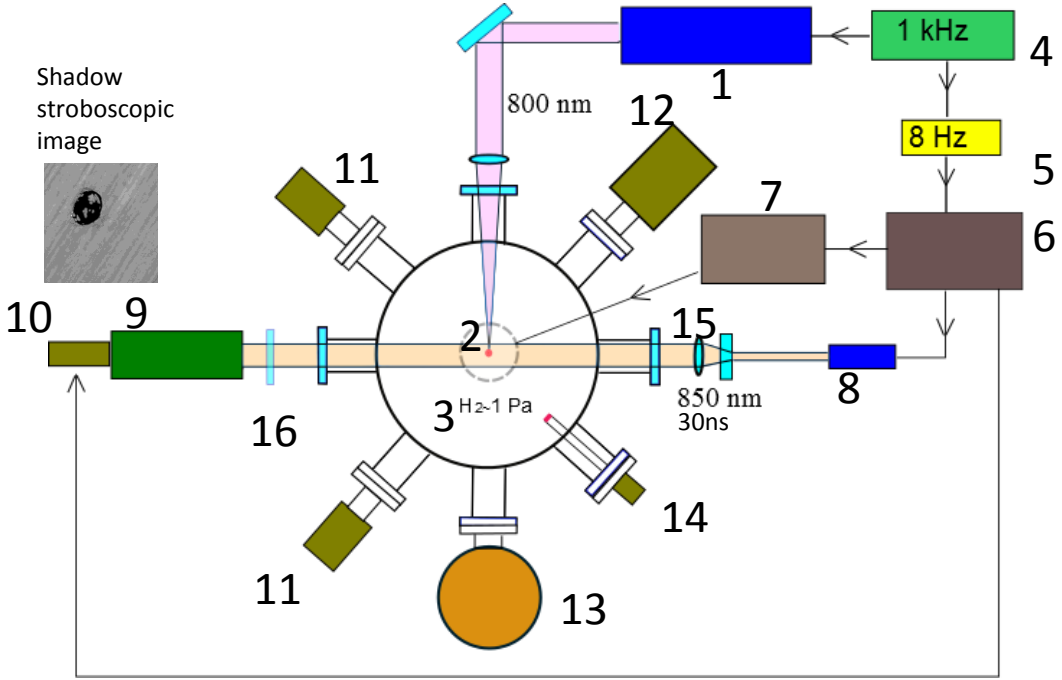


CYMER
An ASML company

I. Fomenkov, EUVL Workshop, Maui 2015

Experimental setup at ISAN





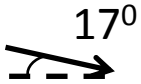
1- FS laser, 2- DG, 3- vacuum chamber, 4- driving generator, 5- frequency divider, 6-delay generator, 7- DG controller, 8- diode laser (IL30C, 850nm, 30ns), 9- long distance microscope (K2 DistaMax), 10-CCD camera (Manta MG-145B), 11- Faraday cup, 12- ion spectrograph, 13- pump, 14- tungsten filament, 15- beam formation optics (diffuser+lens), 16- band pass filter (850nm).

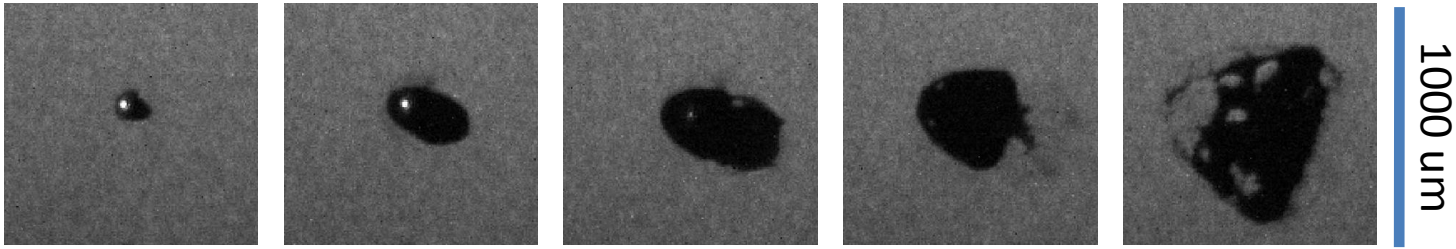
Details: Vinokhodov et al. EUV Source workshop, Dublin 2014

Experimental results

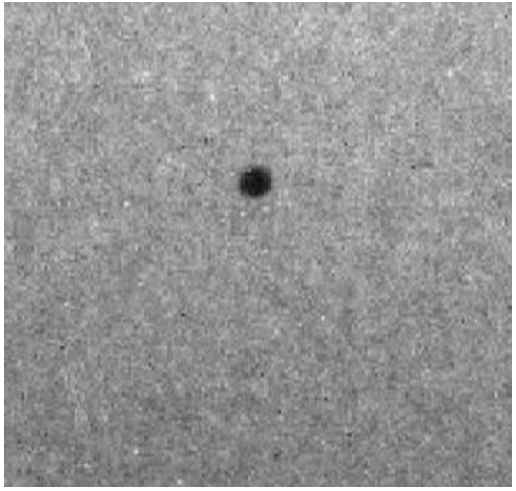
Delay after laser pulse: 0.2 us 0.5 us 0.7 us 1 us 2 us

Laser beam direction



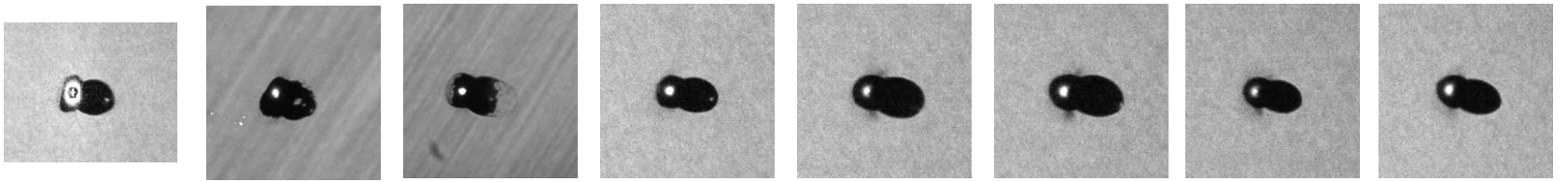


Droplet size	40 μm
Focal spot	50 μm (FWHM)
Pulse length	5.3 ps (FWHM)
Pulse energy	2.3 mJ (-> $2*10^{13}$ W/cm^2, 120 J/cm^2)



Pulse length variation

Delay after laser pulse 0.7 μs



50 fs | 100 fs | 200 fs | 400 fs | 800 fs | 1.5 ps | 3.0 ps | 5.3 ps

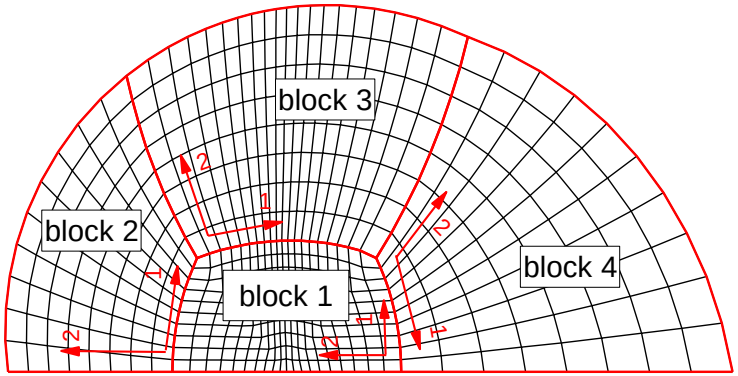
~$2*10^{15}$ W/cm^2 → ~$2*10^{13}$ W/cm^2

RALEF – 2D radiative hydrodynamics code

- **2D hydrodynamics:** a Godunov-type 2nd-order scheme on an adaptive quadrilateral mesh, arbitrary Lagrangian-Eulerian formulation;
- **Thermal conduction:** semi-implicit, fully conservative, 2nd-order on a 9-point stencil;
- **Multi-frequency radiation transport:** S_n method along short characteristics, semi-implicit, non-conservative, 1st order, LTE source function, quasi-static approximation;
- **EOS:** a variety of options for the equation of state;
- **Spectral opacities:** provided by the THERMOS code (KIAM, Novikov et al.);
- **Laser absorption:** no refraction, no reflection, inverse-bremsstrahlung absorption (with artificial enhancement beyond the critical surface) along short characteristics;

Simulation setup

Quasi-half-sphere mesh: 100 000 cells



Initial conditions: ρ_0 = 6.1 g/cc, p_0 = 2 mbar, T_0 = 0.1 eV

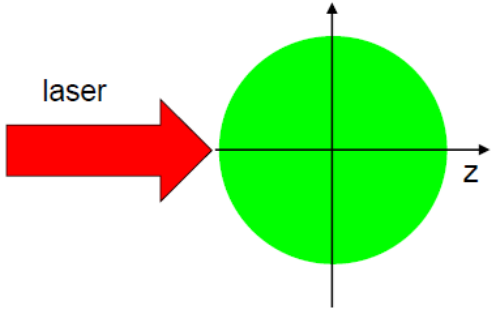
Boundary conditions: free outflow

EOS: QEOS-type (R.M.More *et al*; present version by S.Faik, Frankfurt), Maxwell construction in the two-phase region, empirical energy of vaporization

Thermal conductivity: semi-empirical, matching Spitzer with metal at room temperature

Radiation transport: S_8 with 24 spectral groups

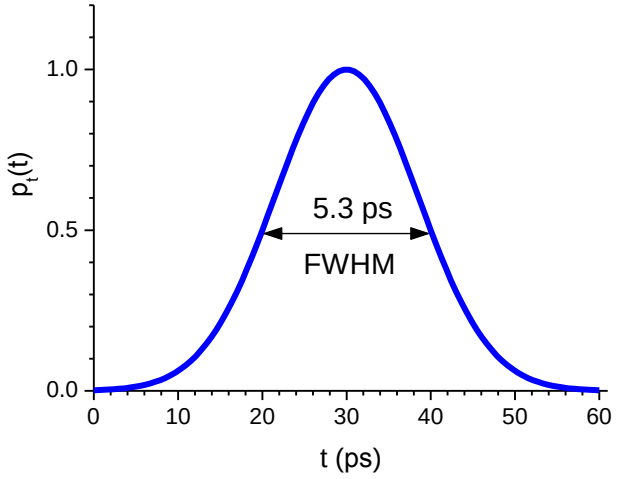
Input parameters



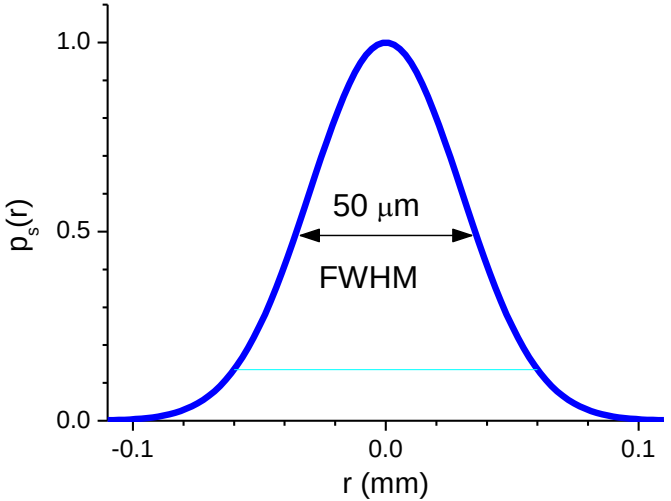
Sn droplet: D_{Sn} = 40 µm

Nominal laser energy: $E_{las\text{-}nominal}$ = 2.3 mJ

Gaussian temporal profile (normalized)



Gaussian spatial profile (normalized)



Laser-induced shockwave

‘Plasma stage’

- Ablation due to laser irradiation
- Thin plasma layer (1-5 um) is formed
- Plasma temperature ~ 100 eV
- Semispherica shockwave is formed by plasma, peak pressure 2.4 mbar

!!! Well above the critical point (kbar scale)

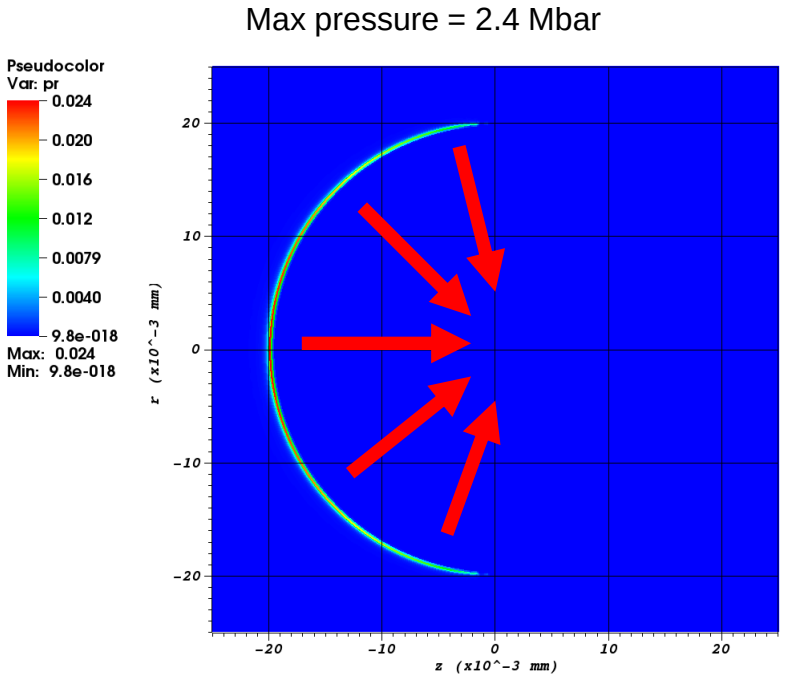
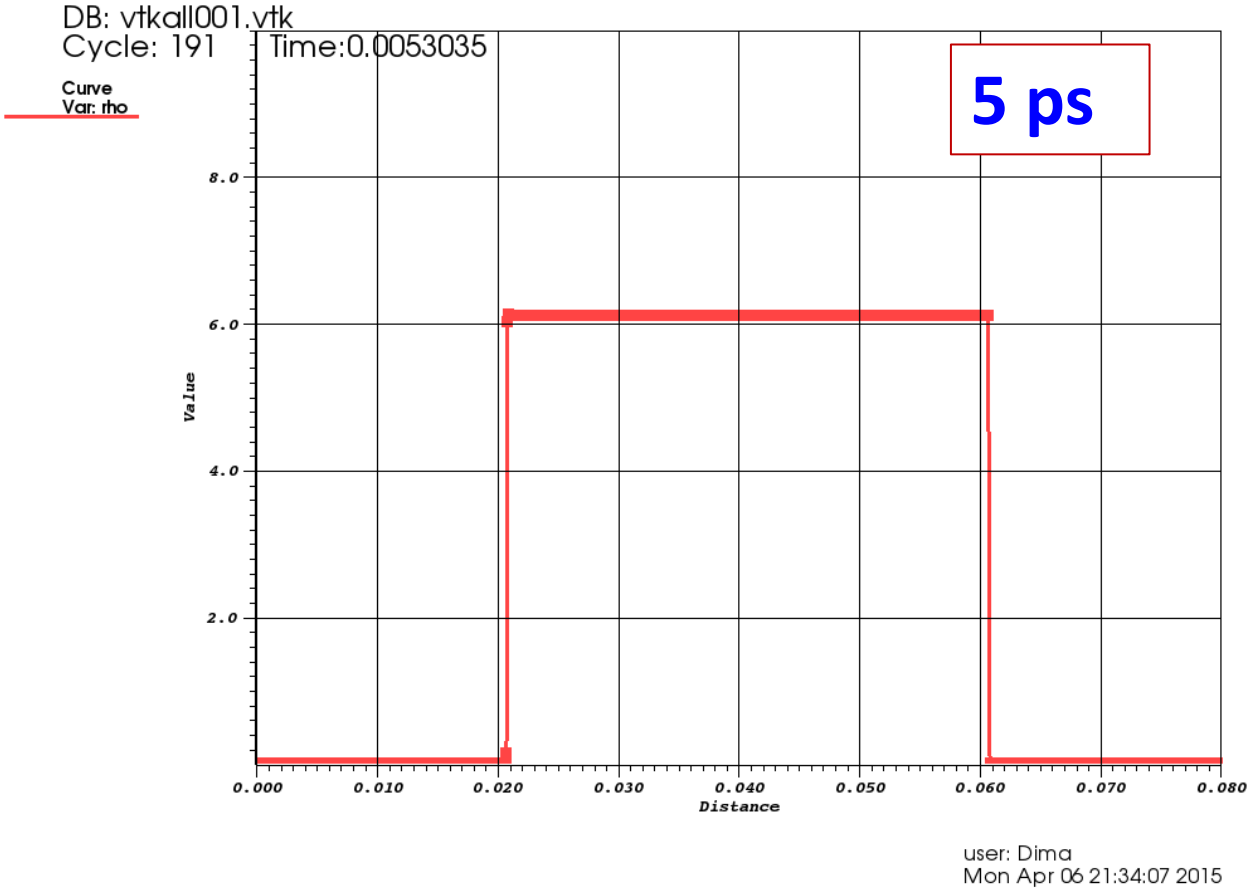
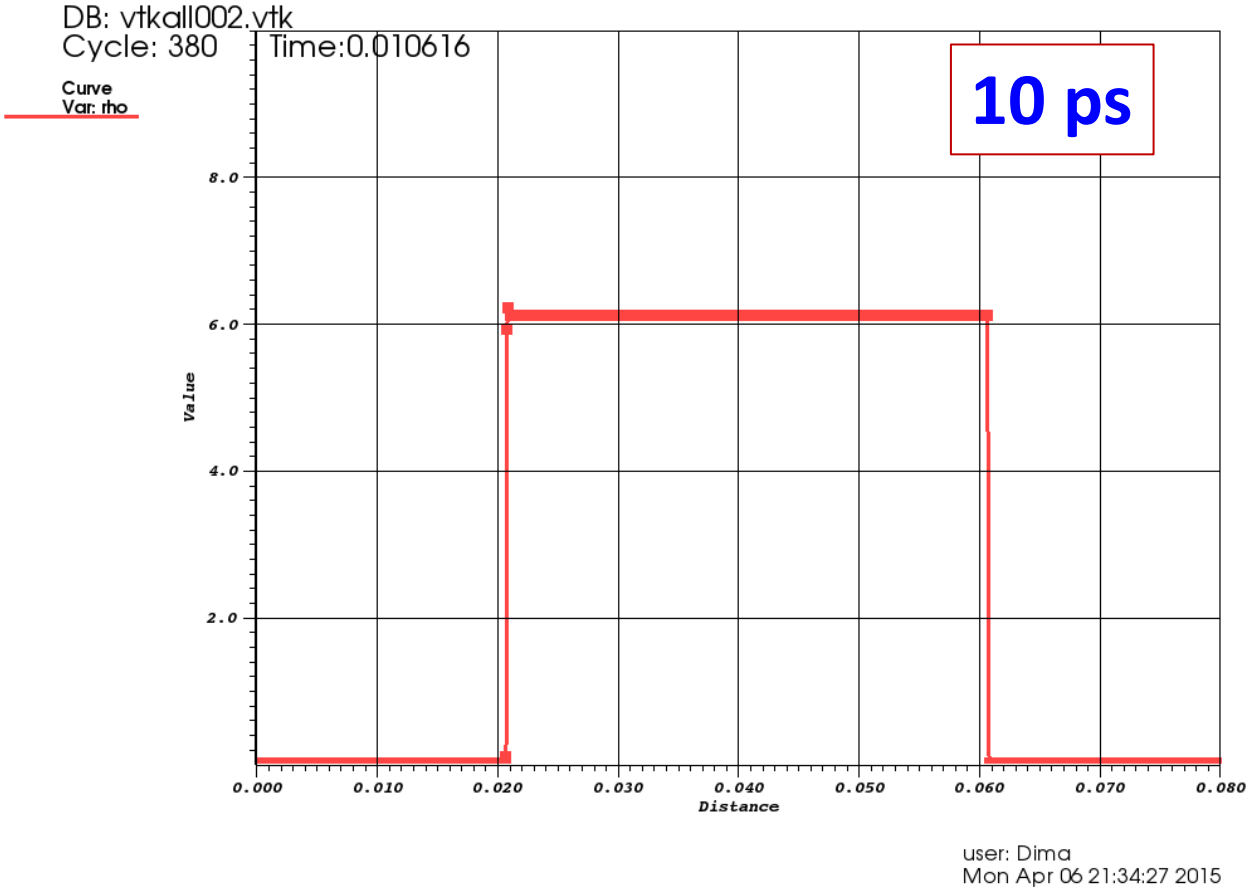


Fig.1 Semi-spherical shock wave in the droplet by the end of the laser pulse (21 ps)

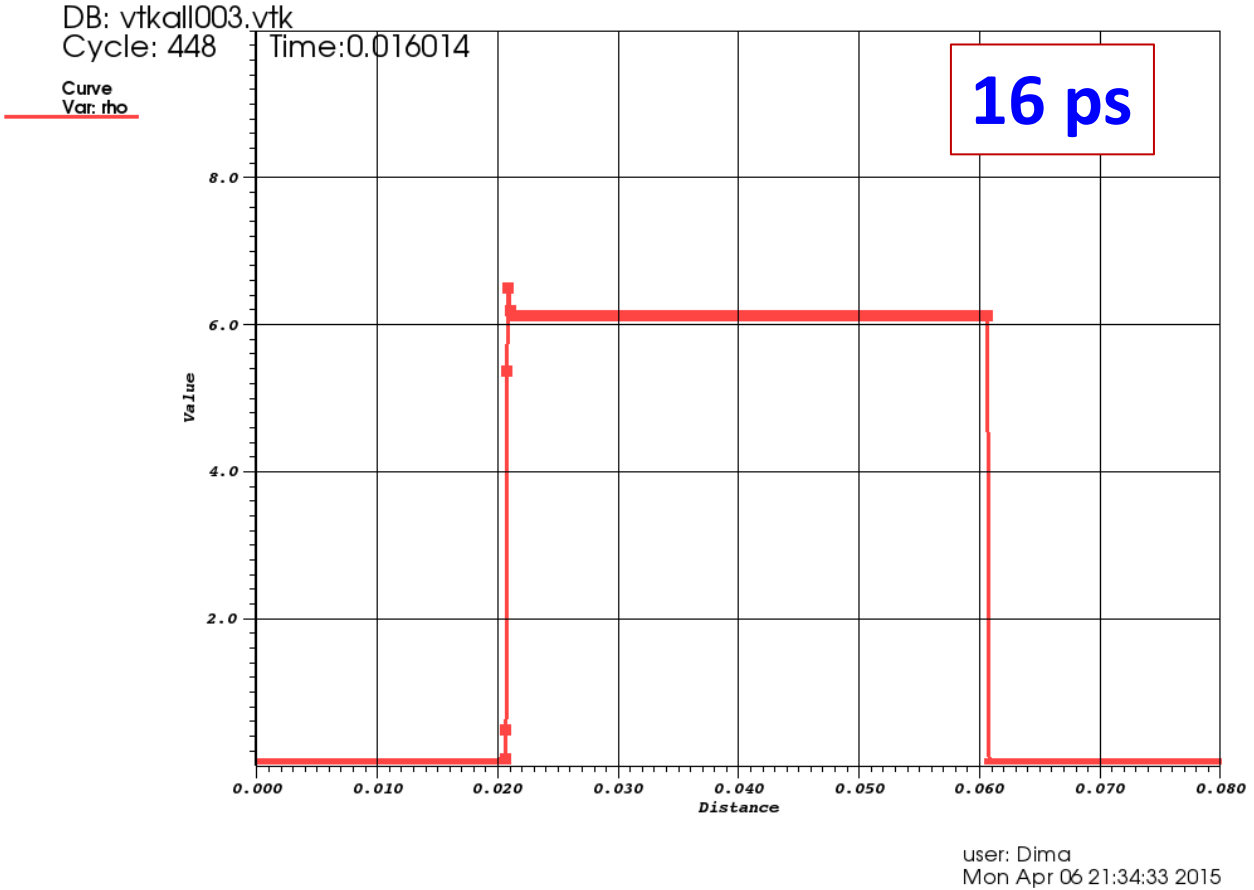
Evolution of density profile



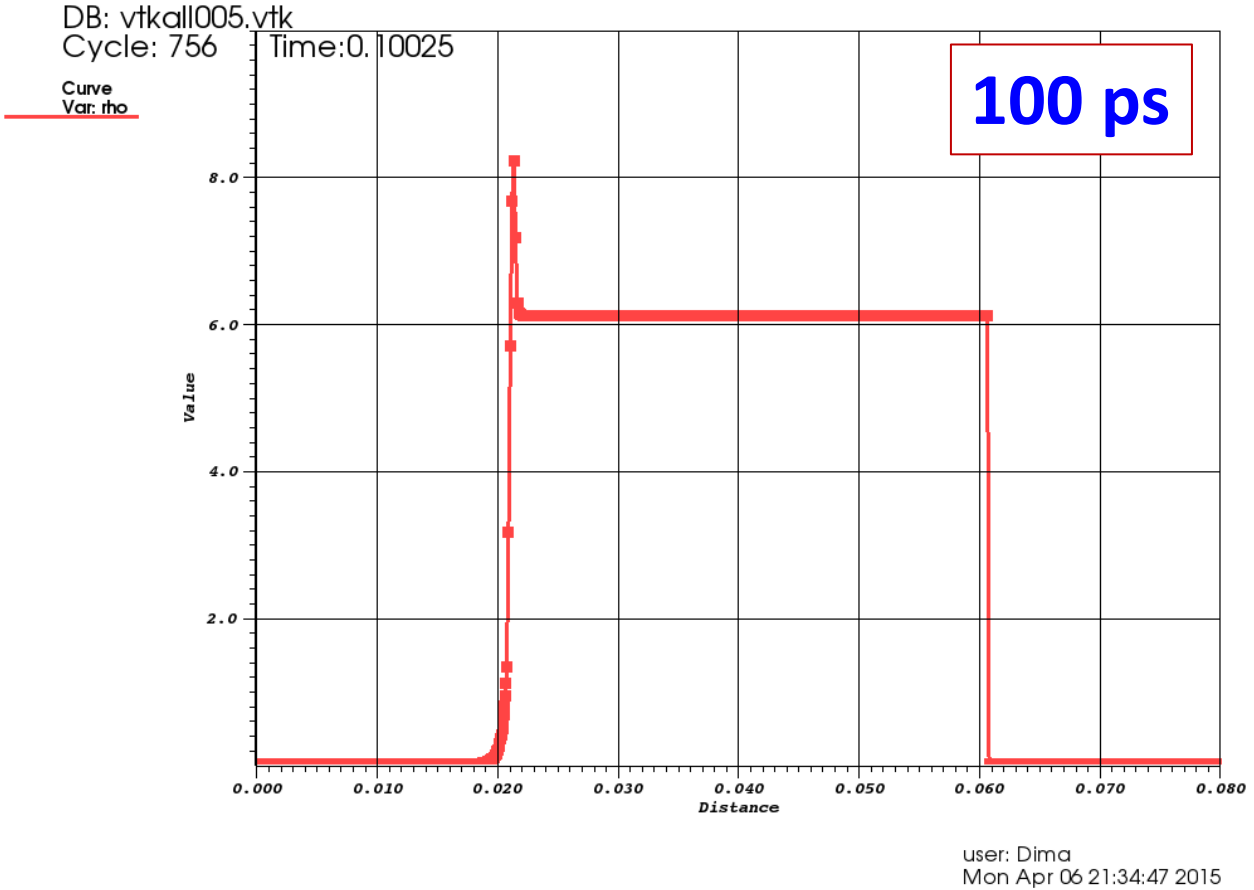
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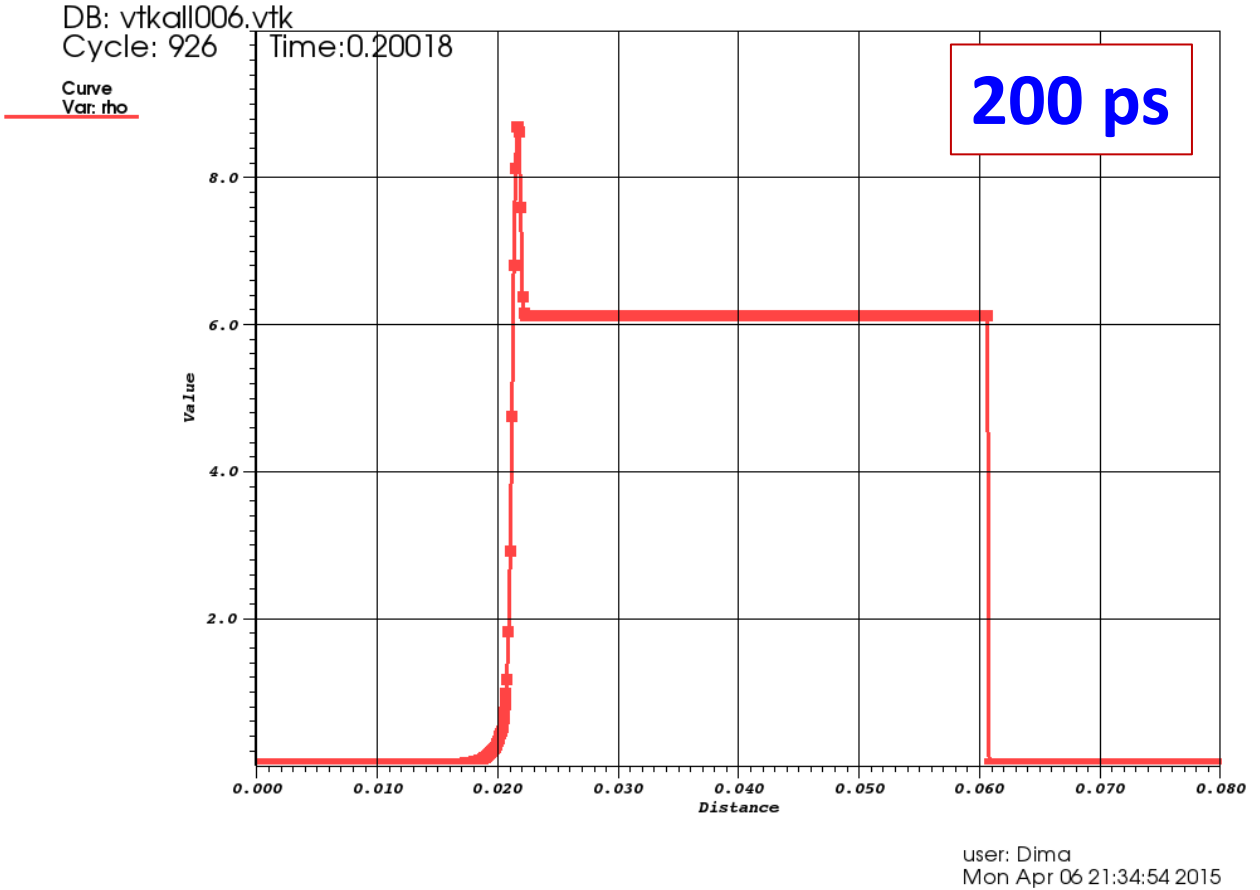
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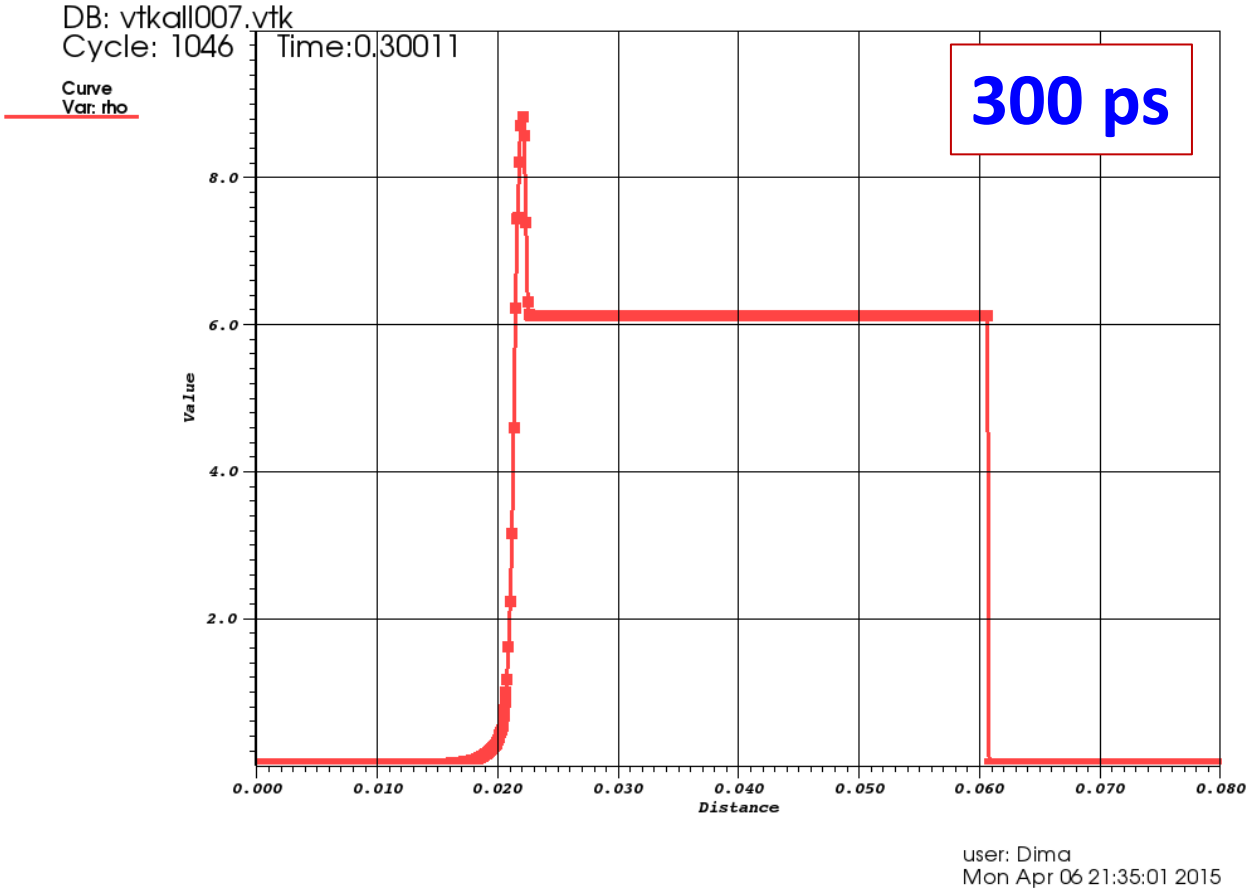
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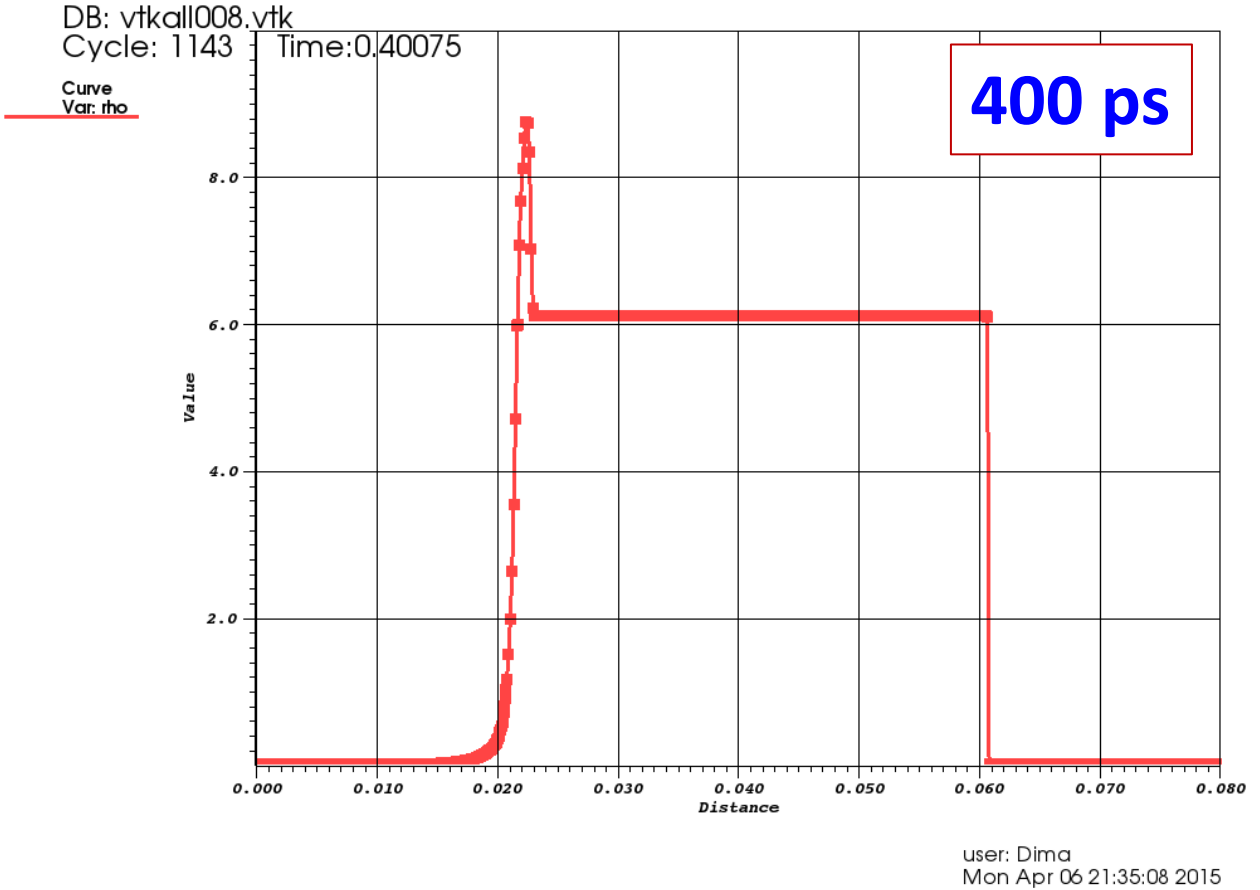
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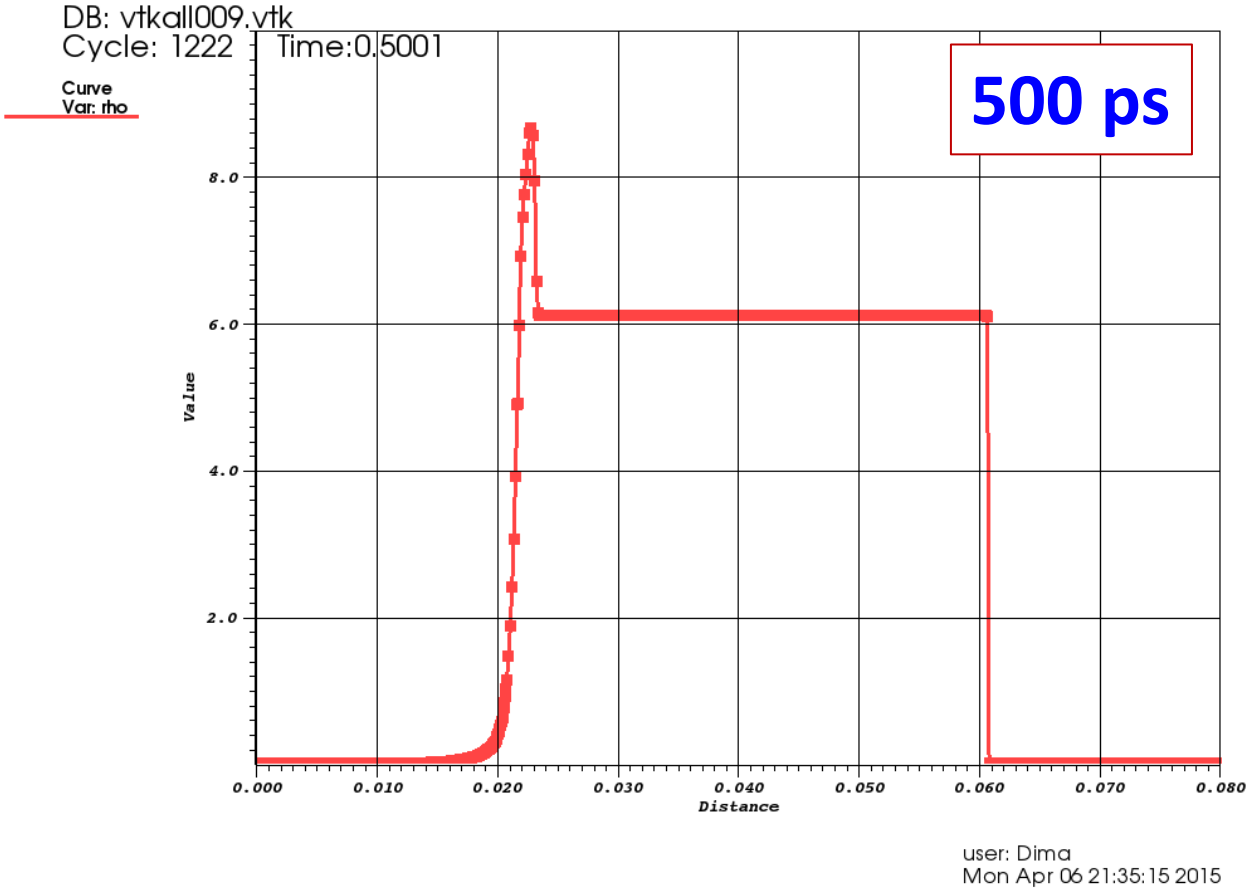
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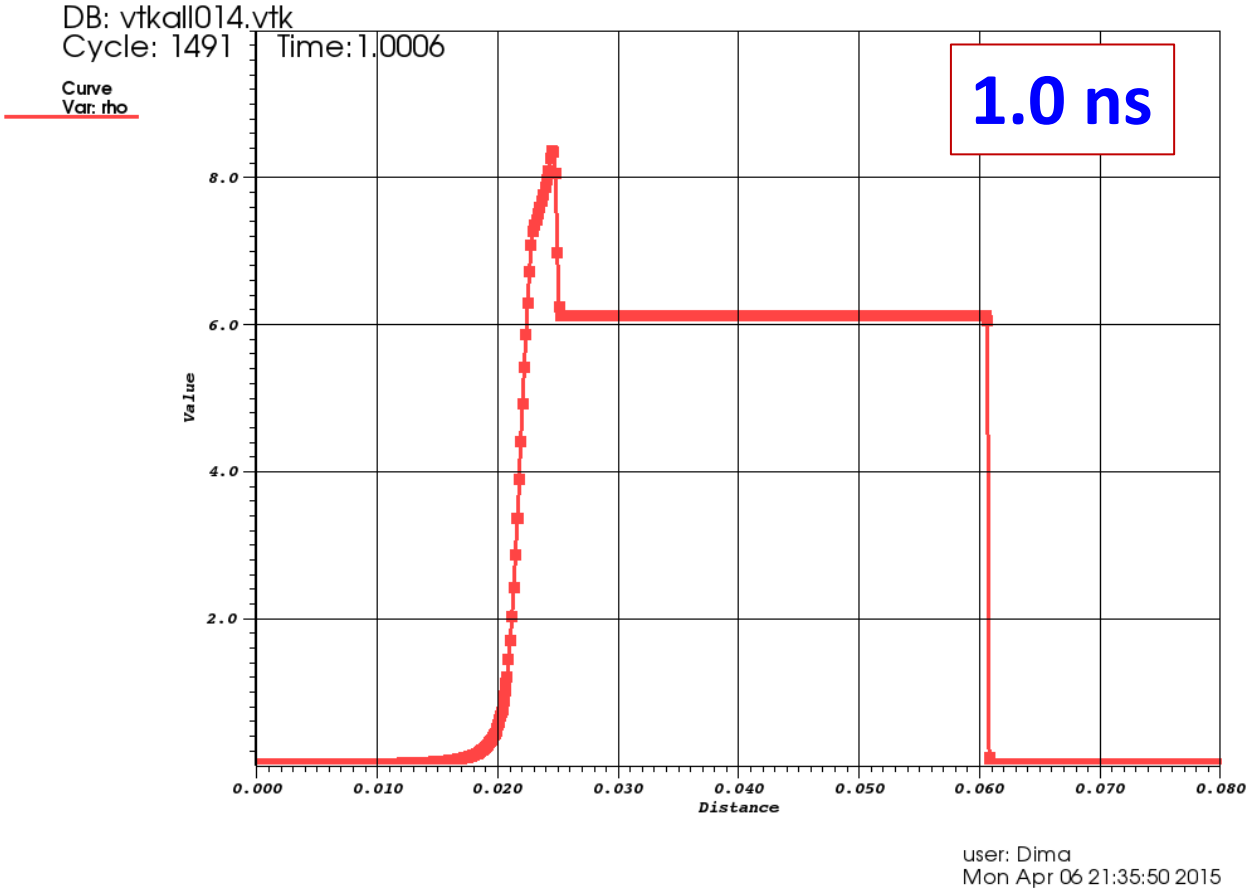
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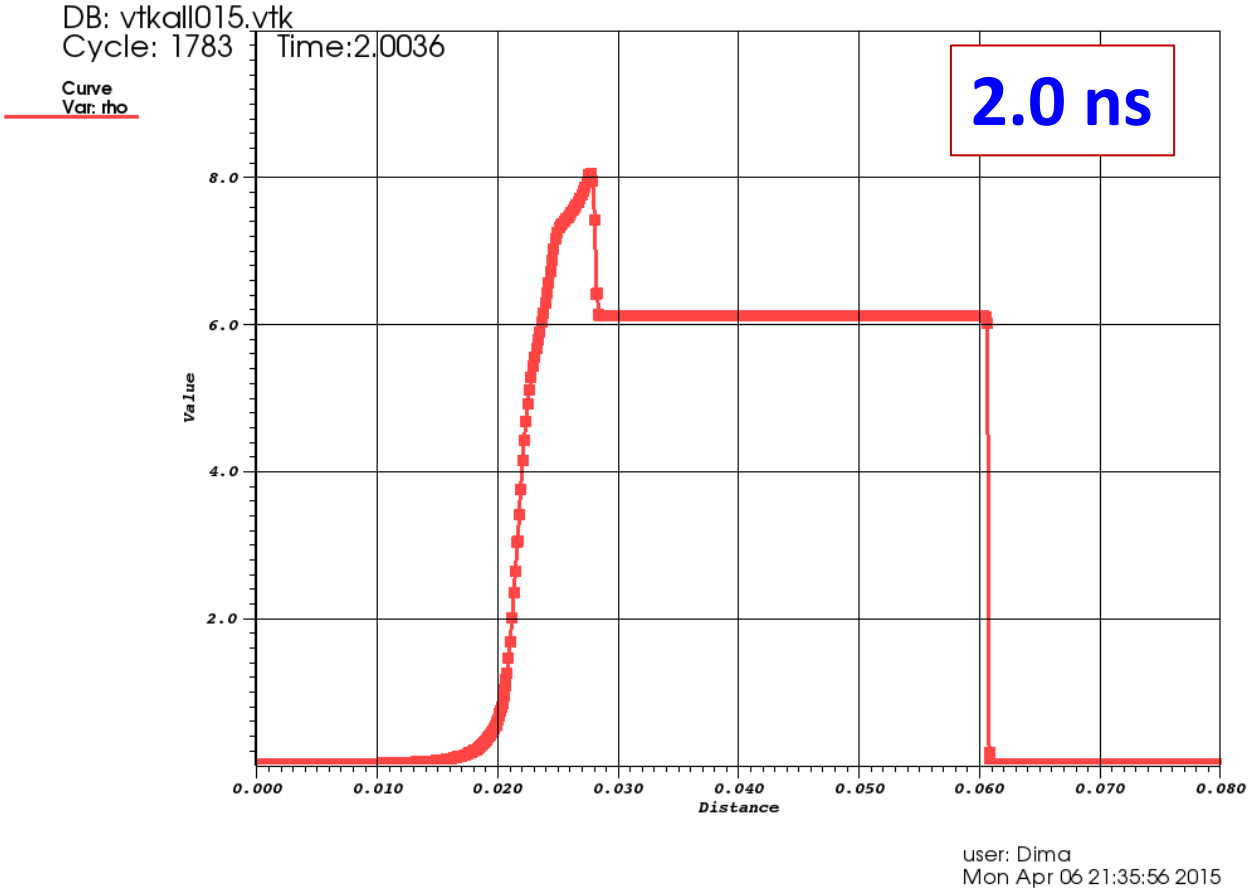
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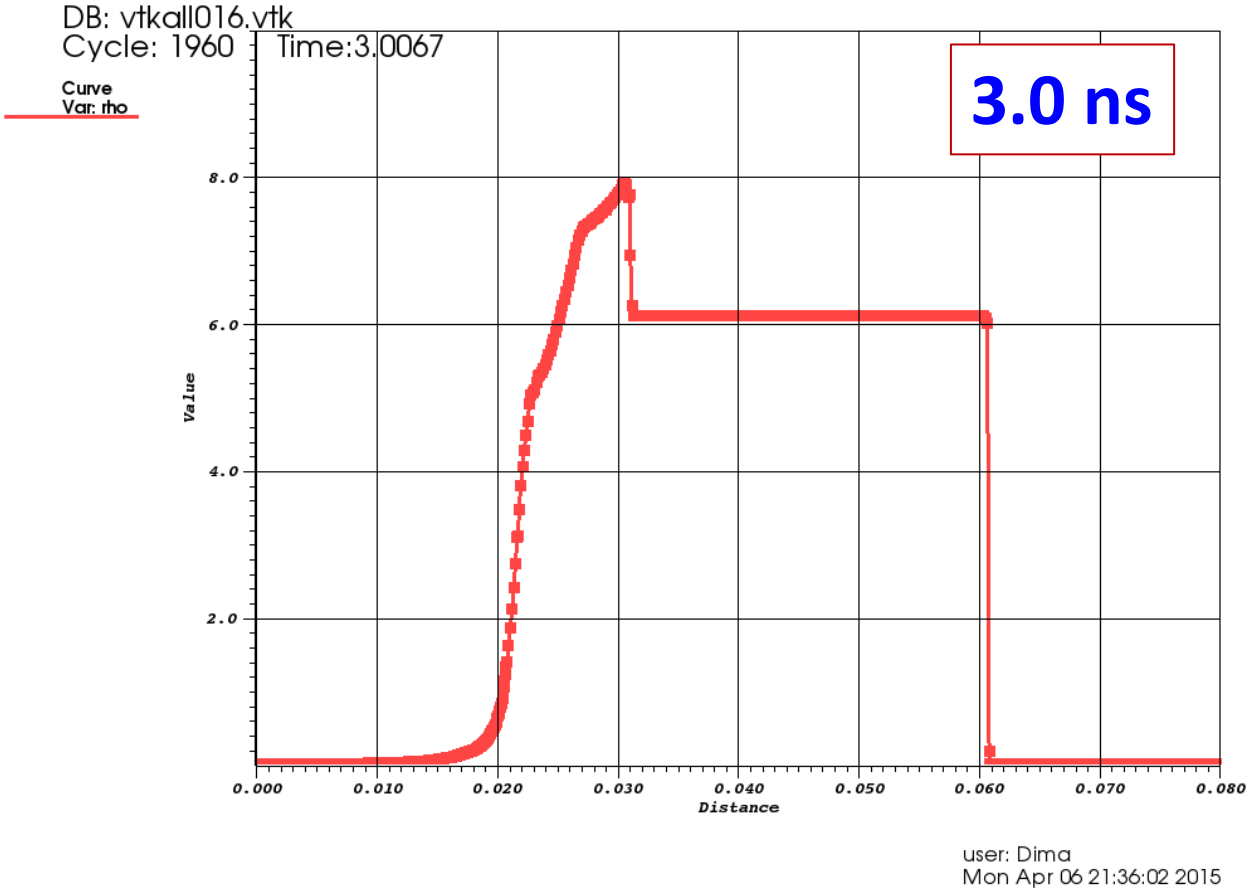
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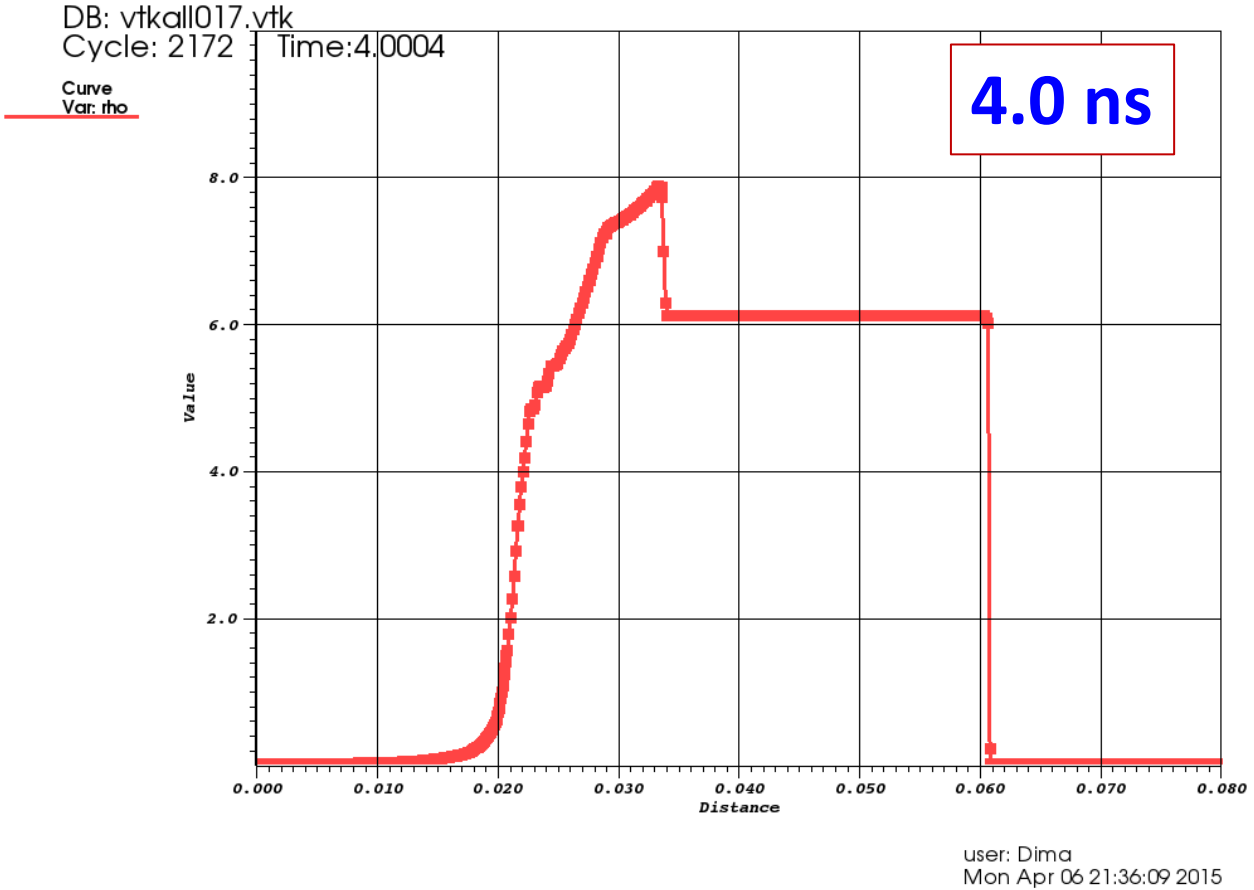
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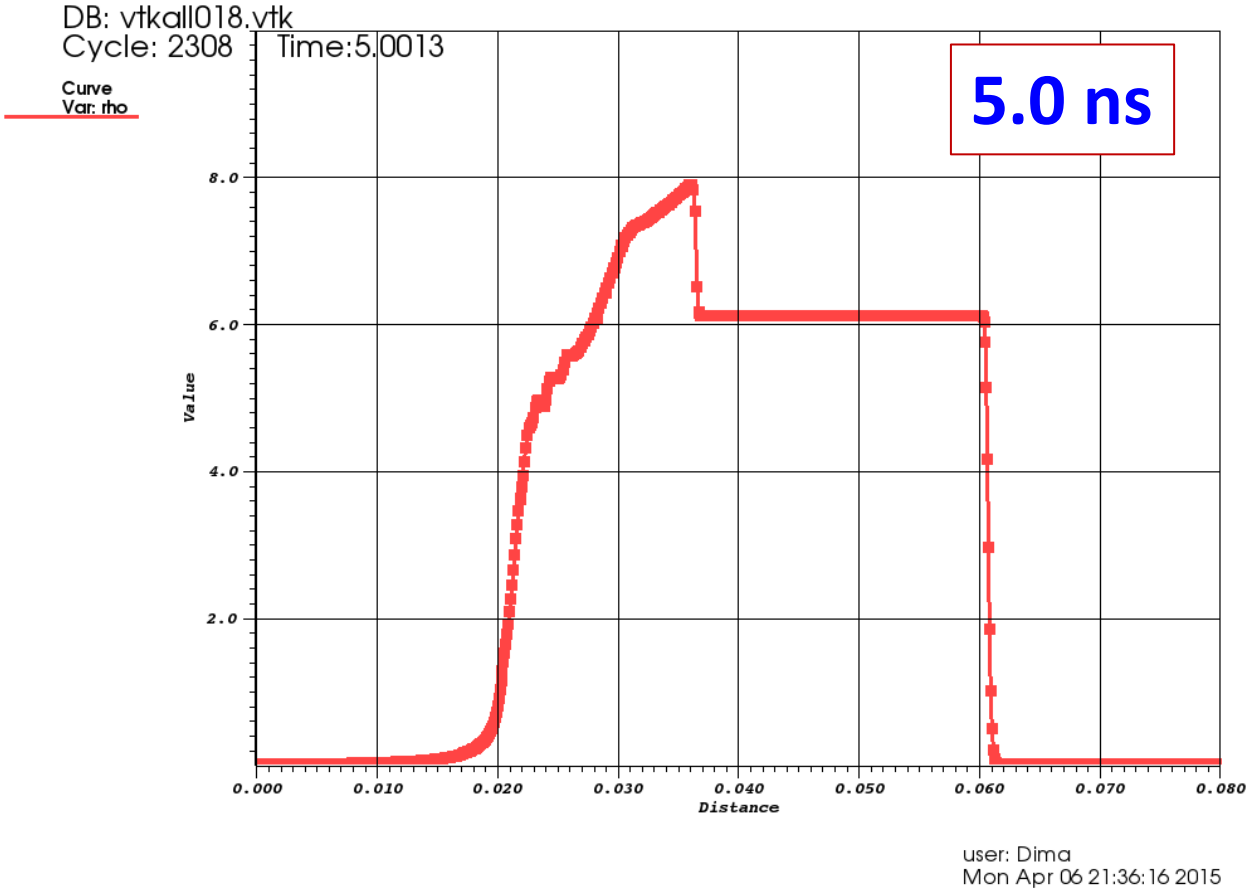
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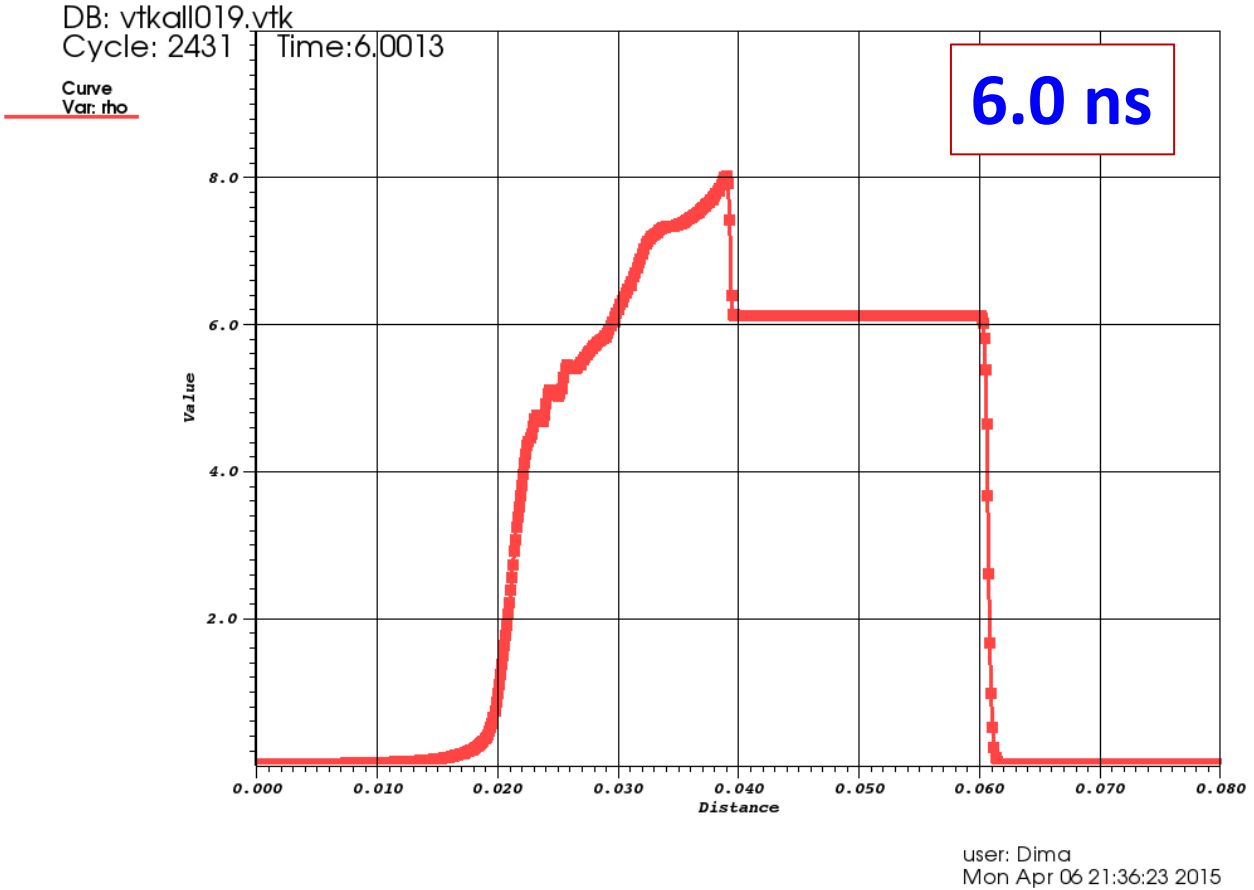
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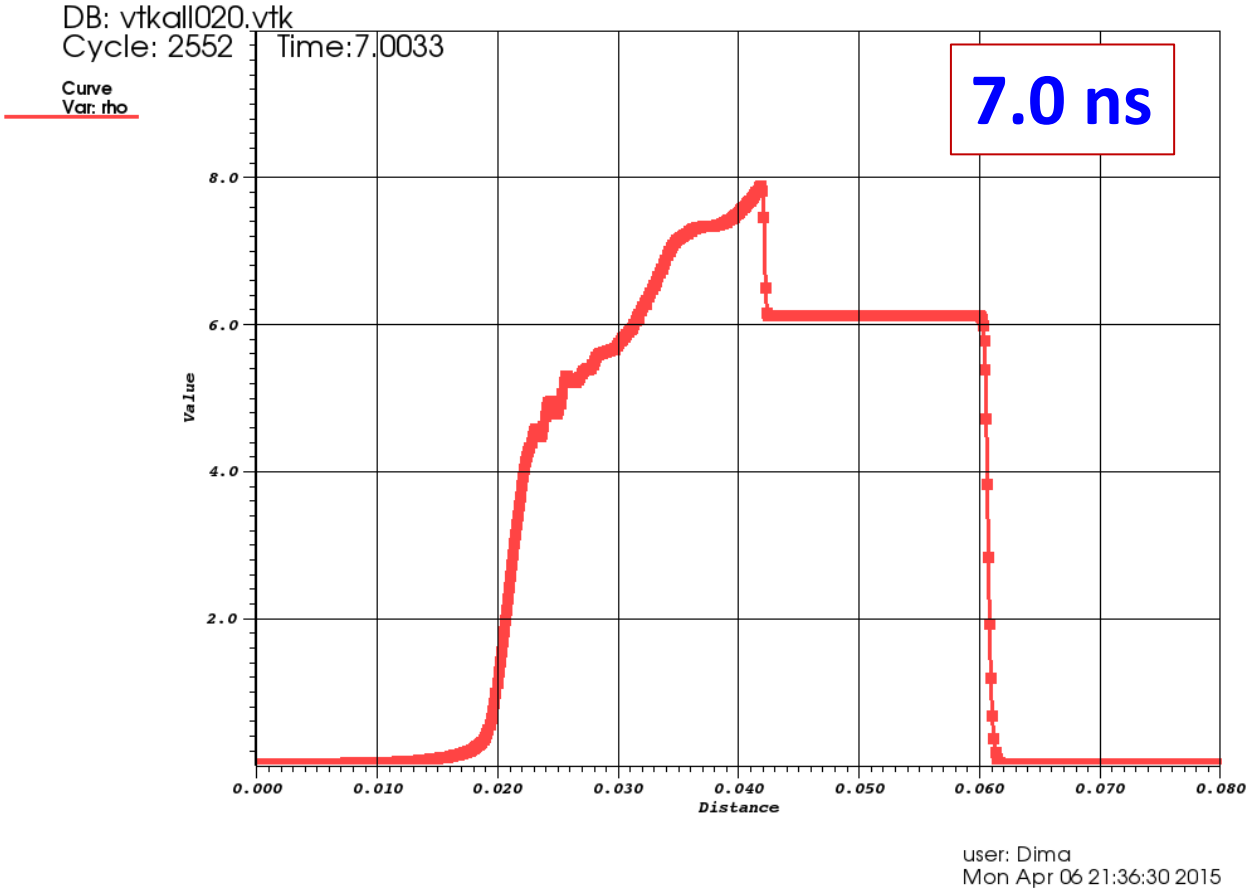
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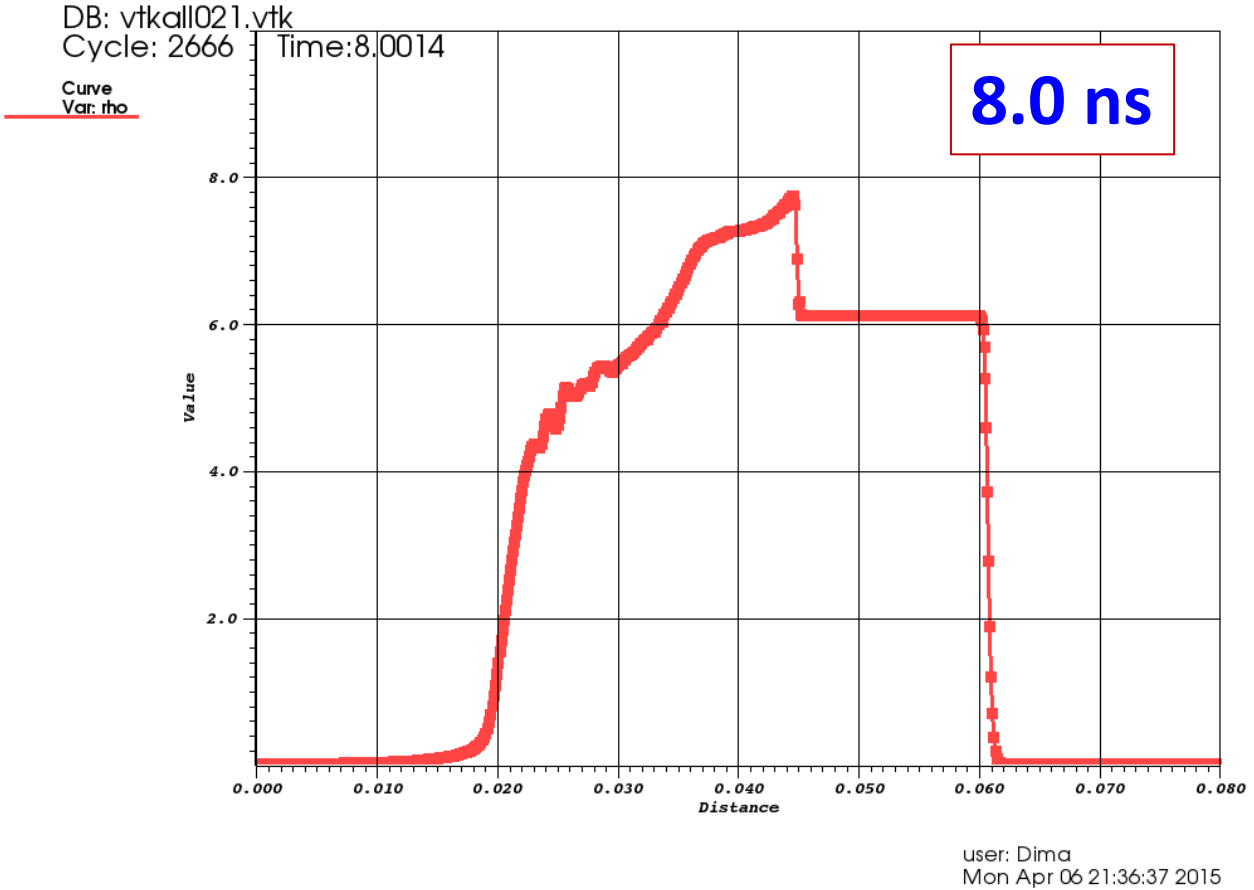
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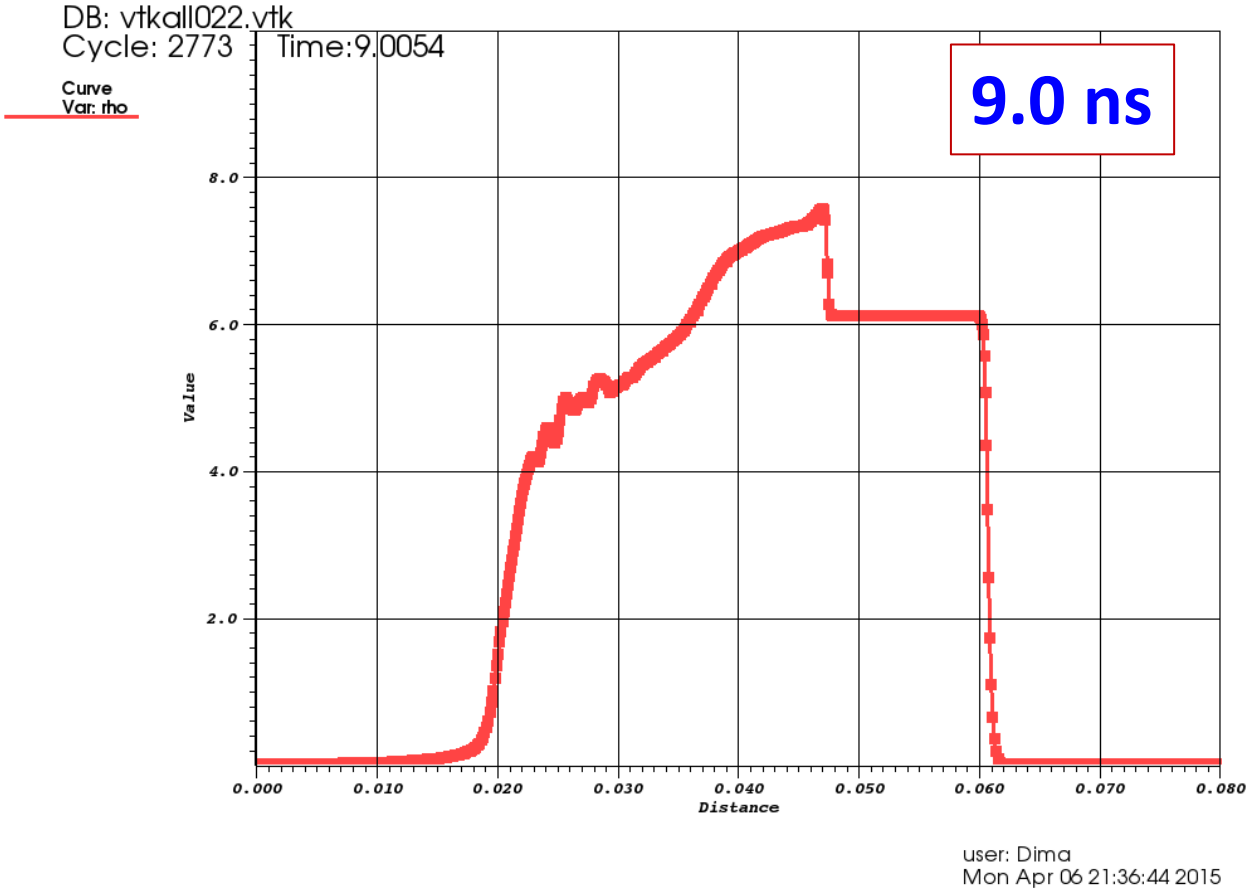
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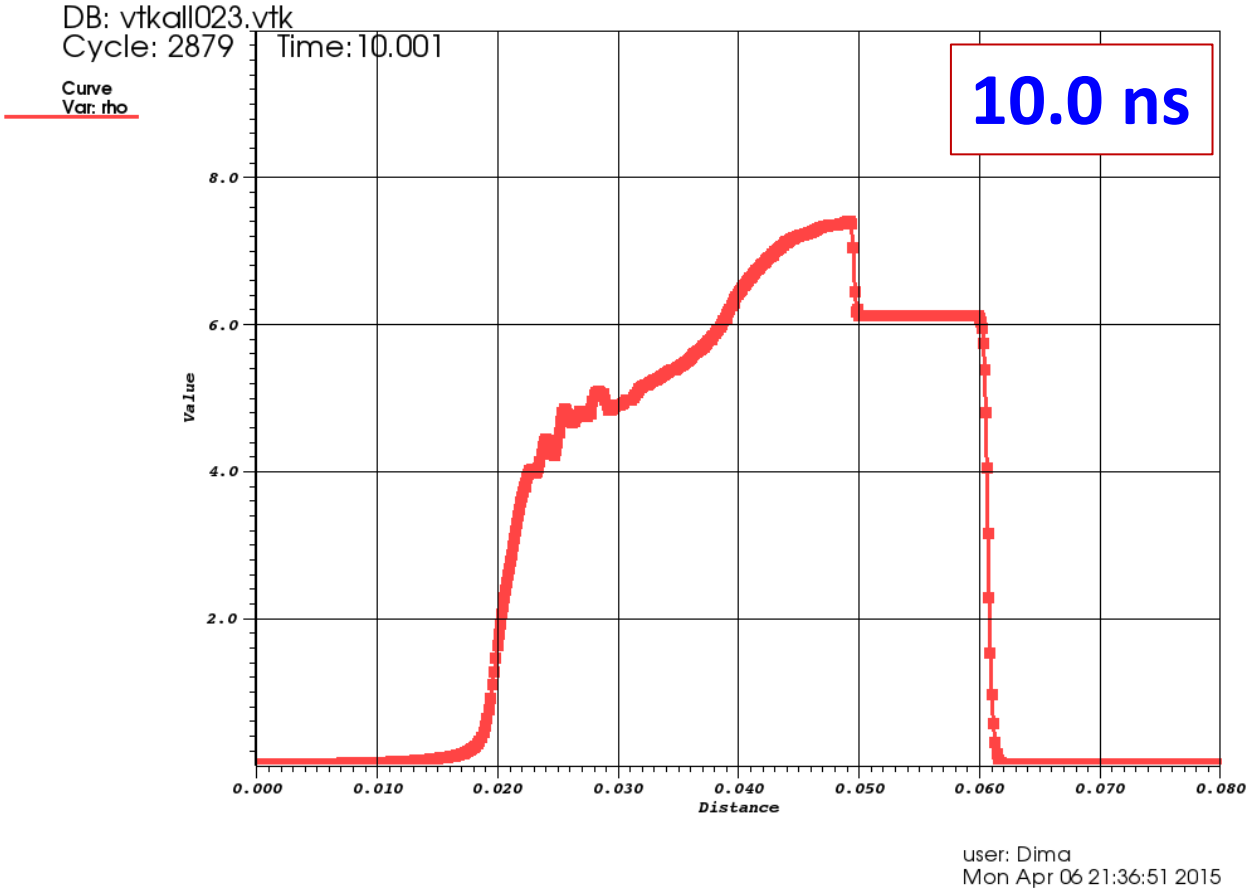
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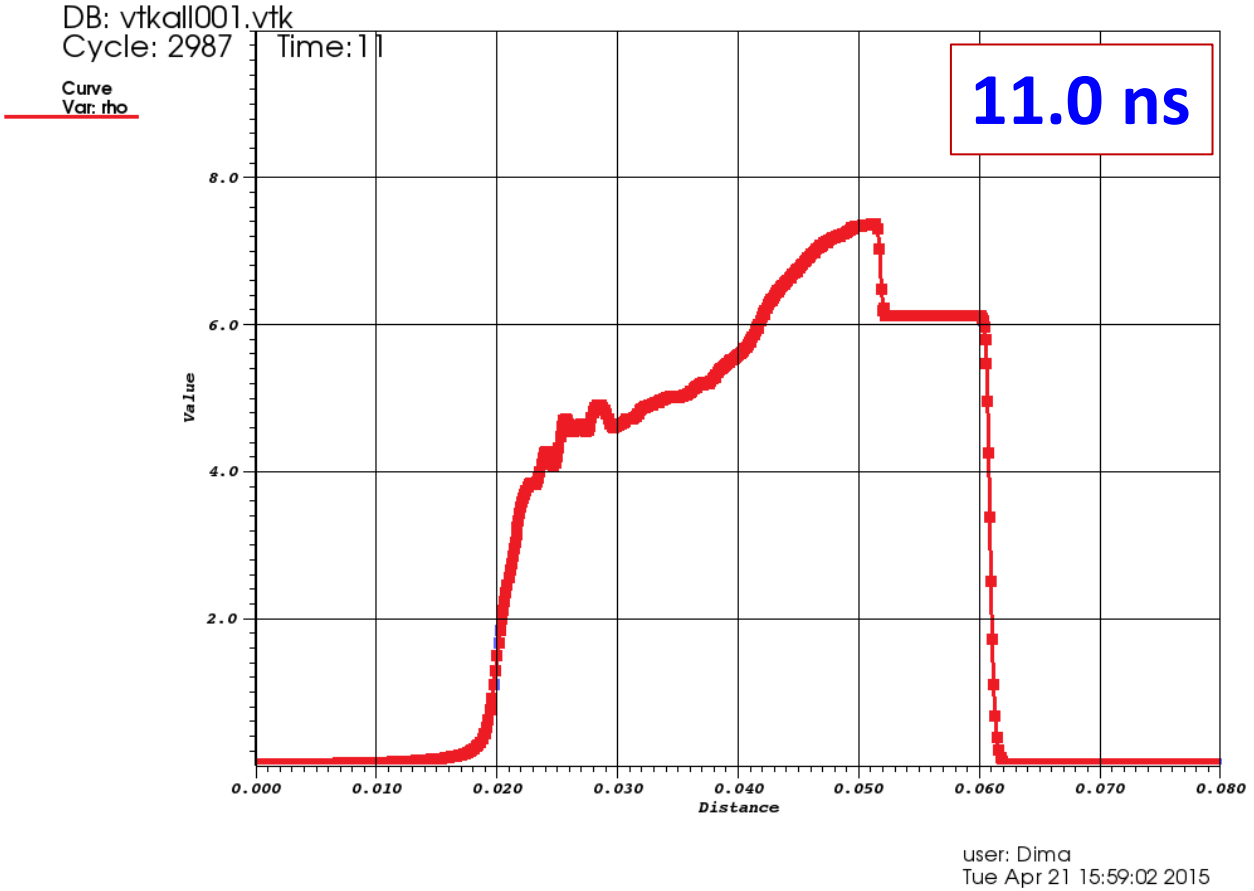
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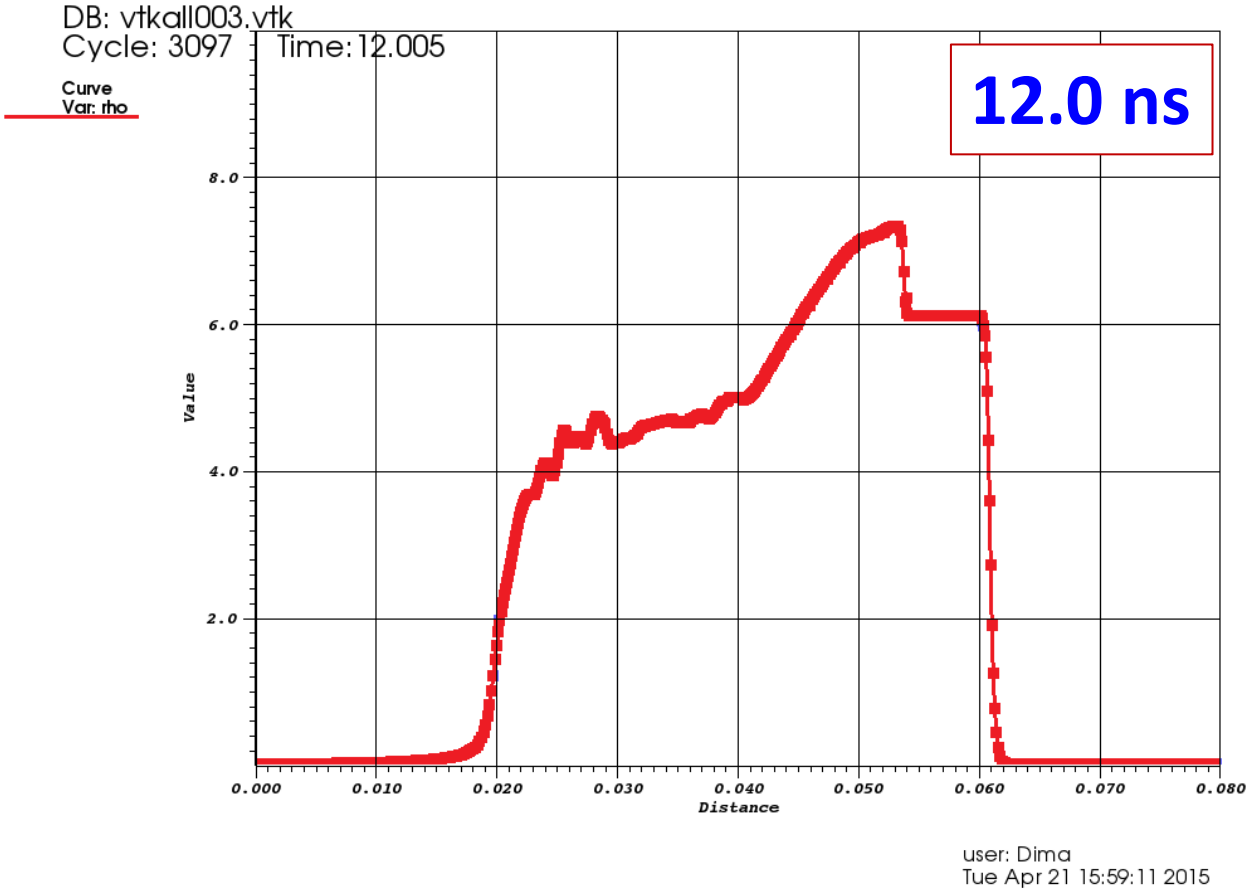
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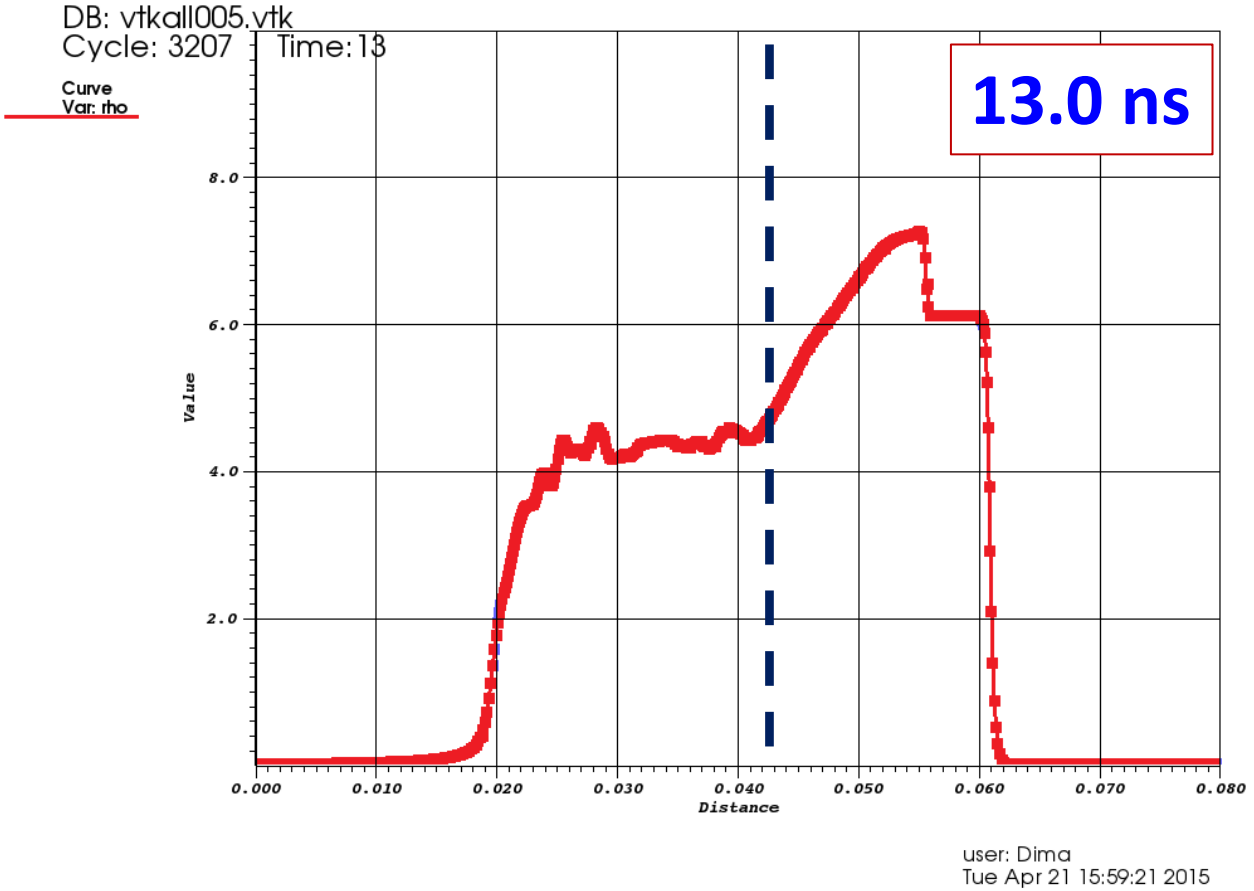
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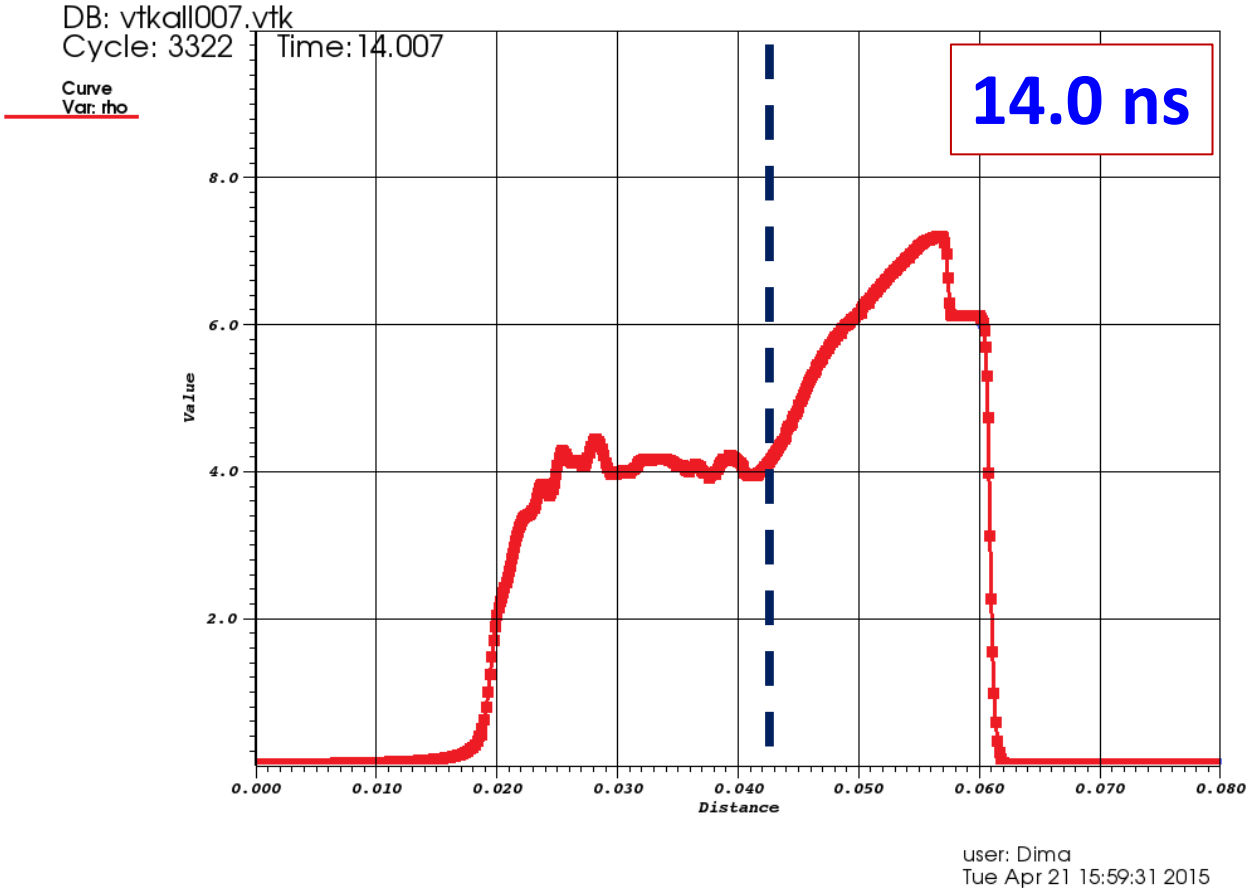
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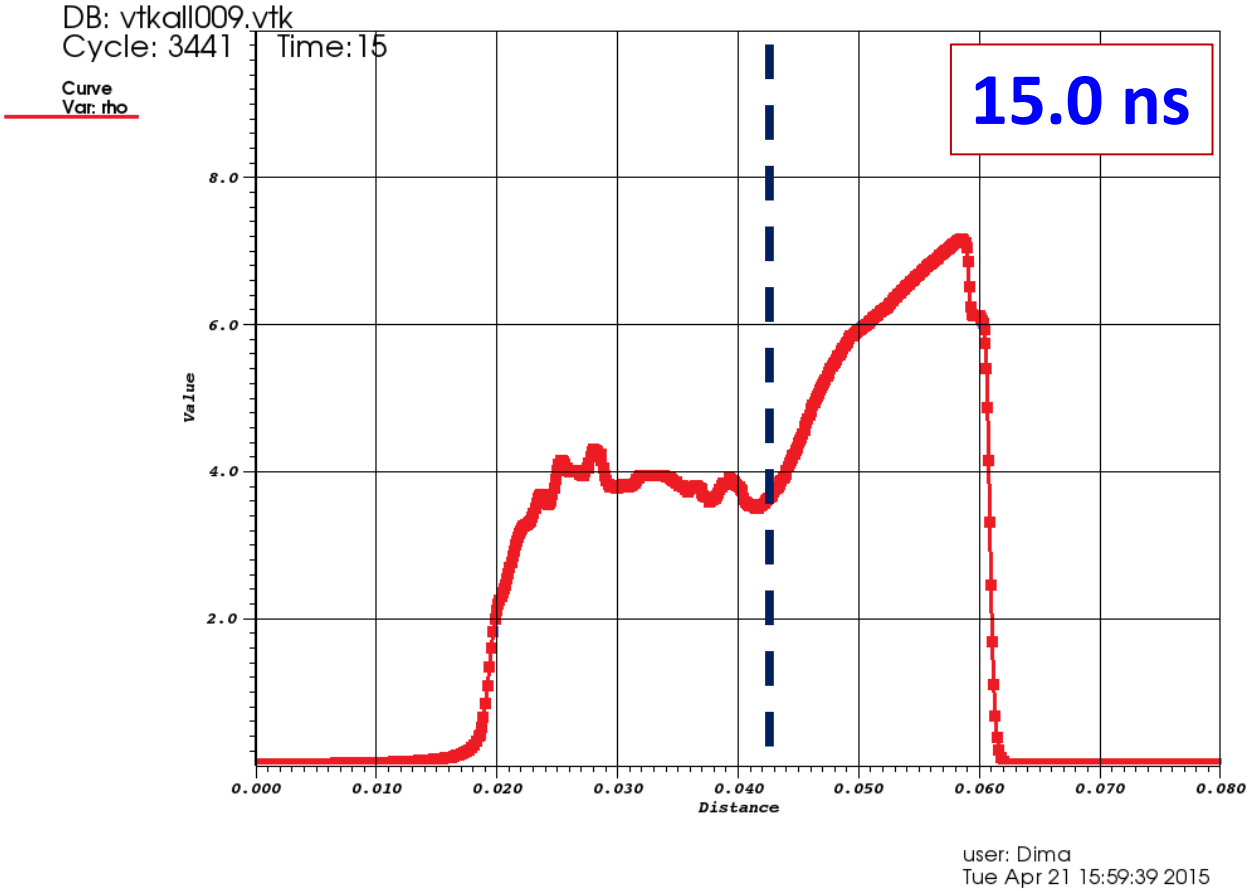
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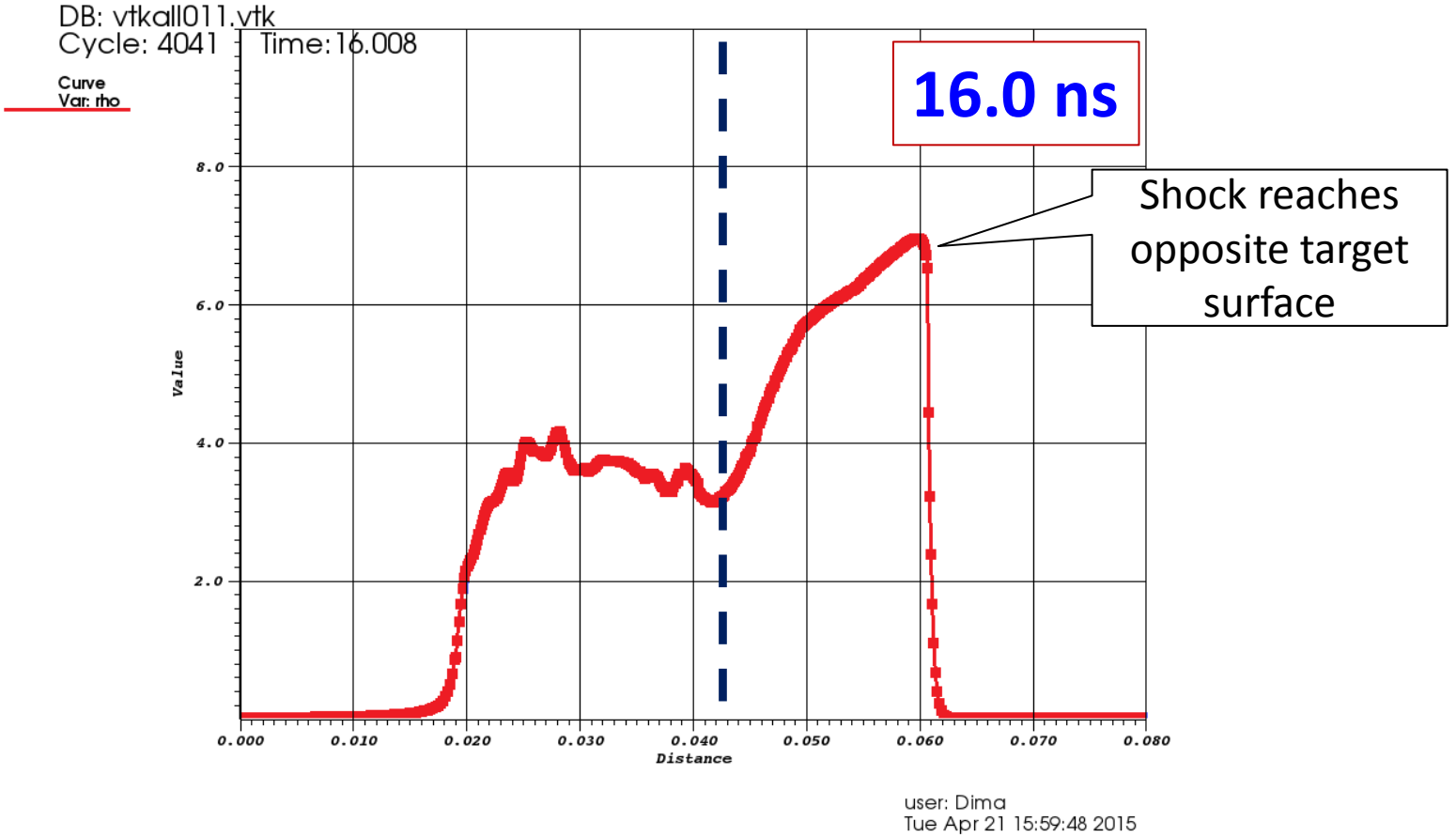
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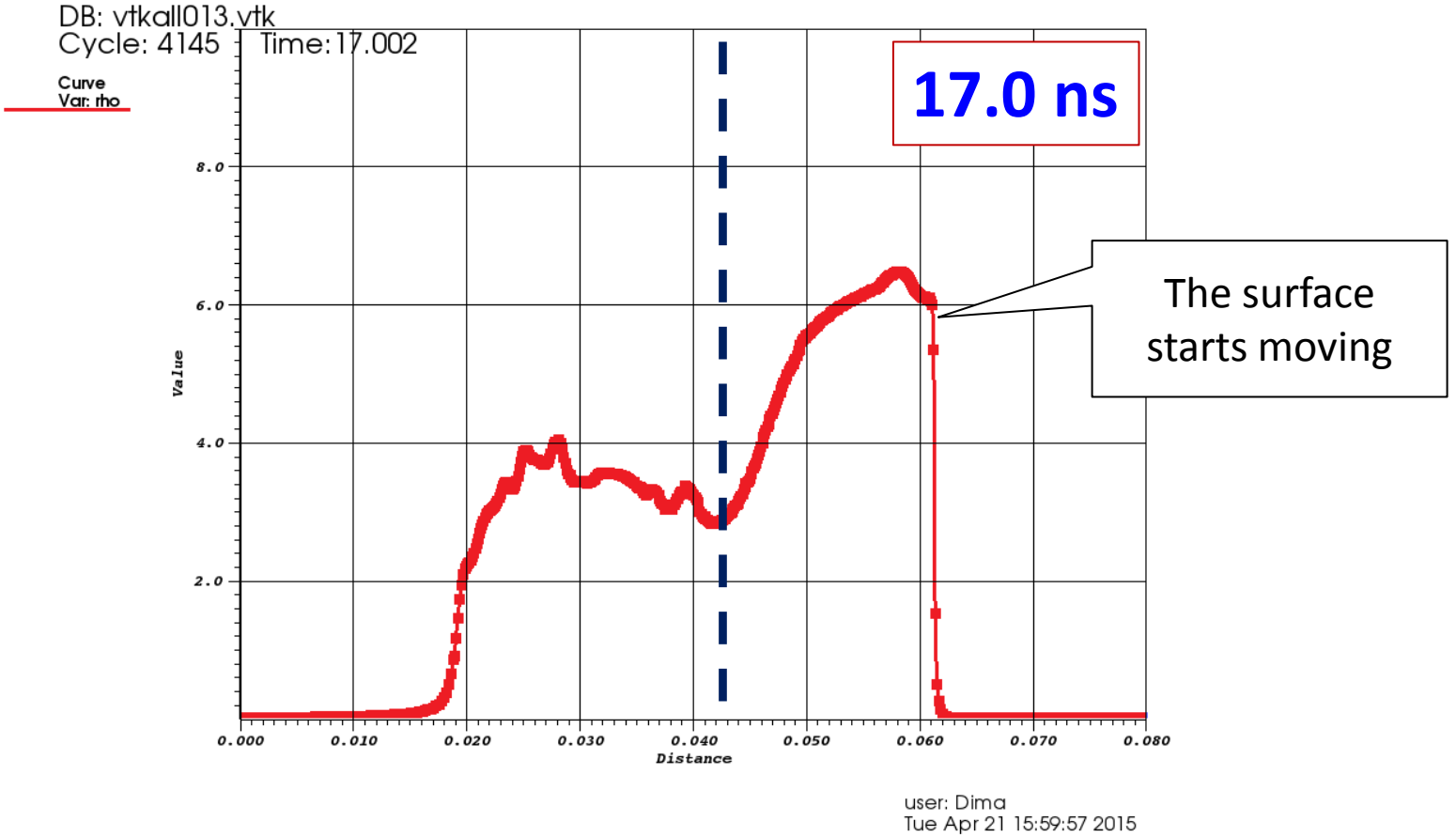
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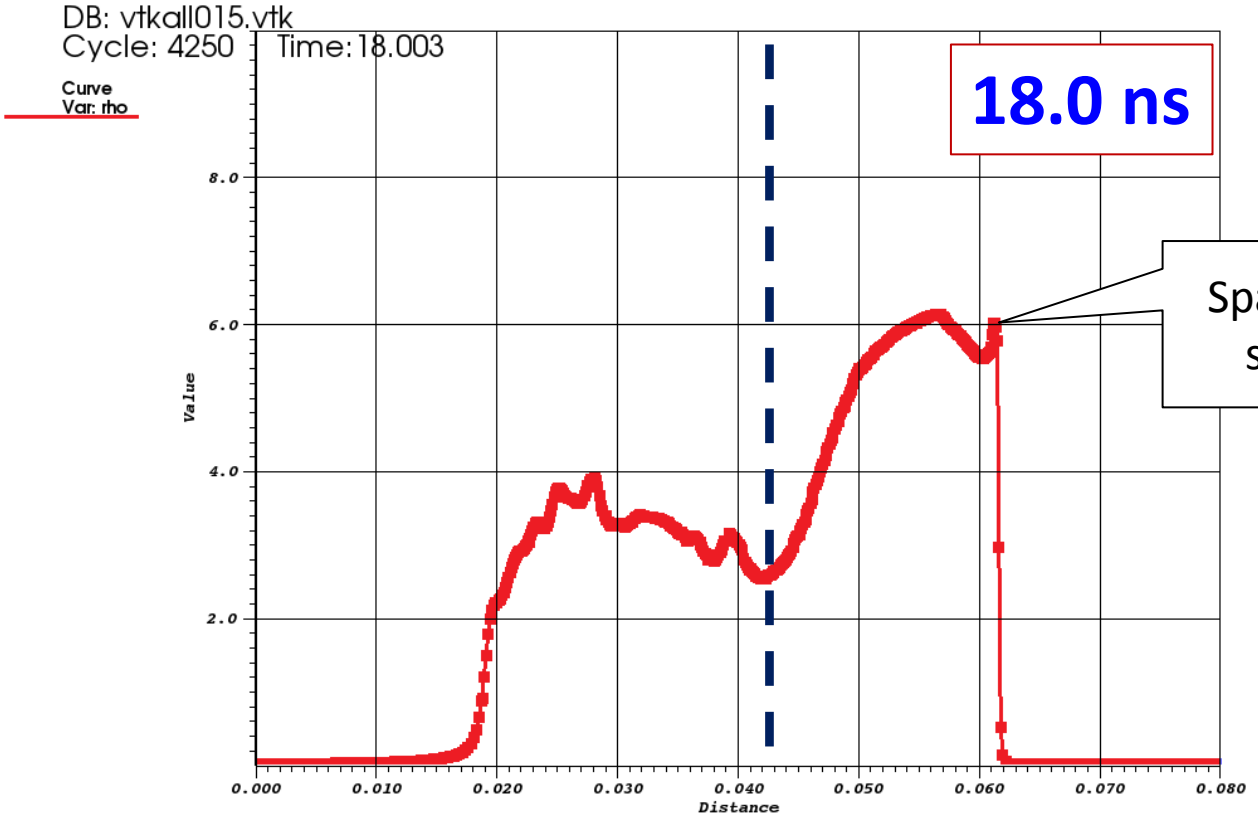
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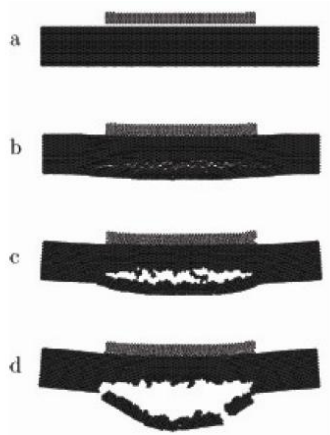


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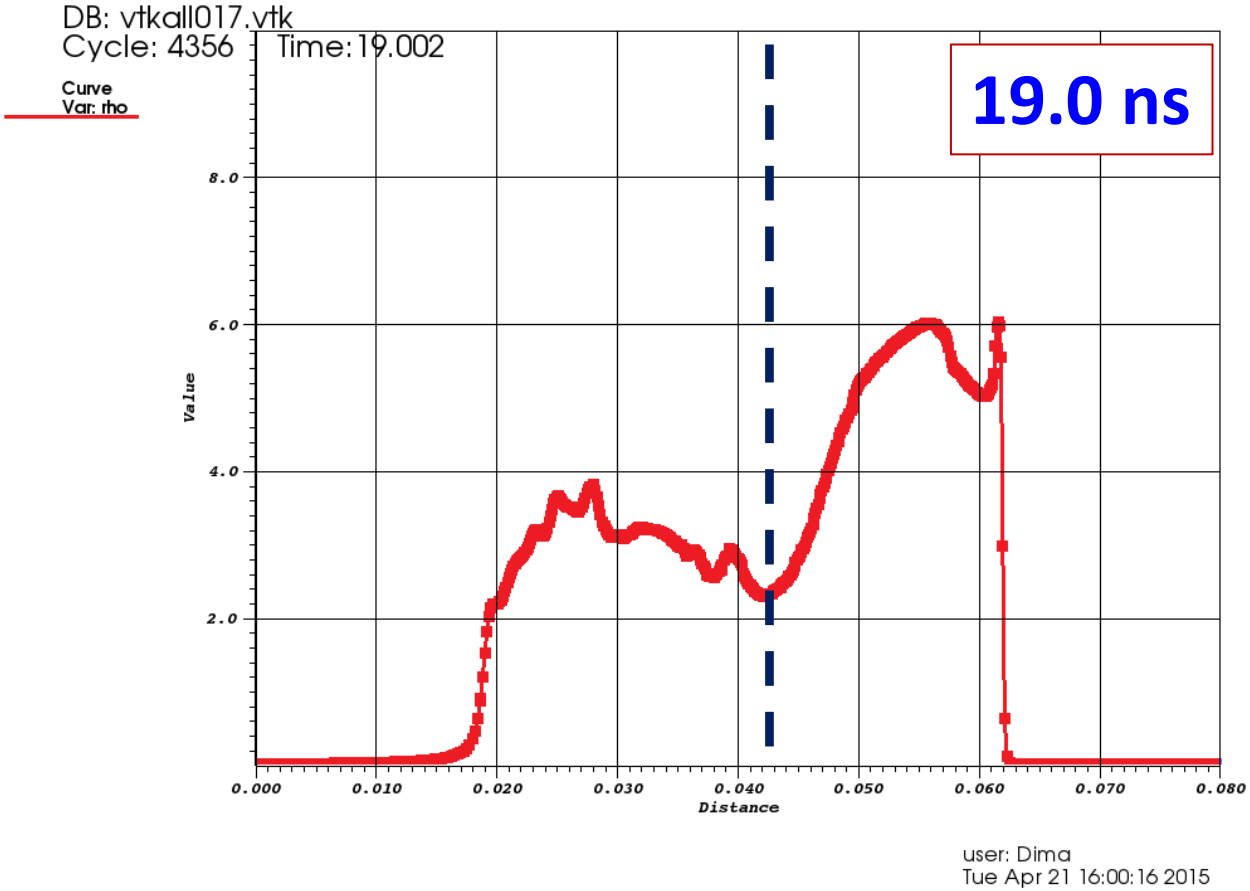


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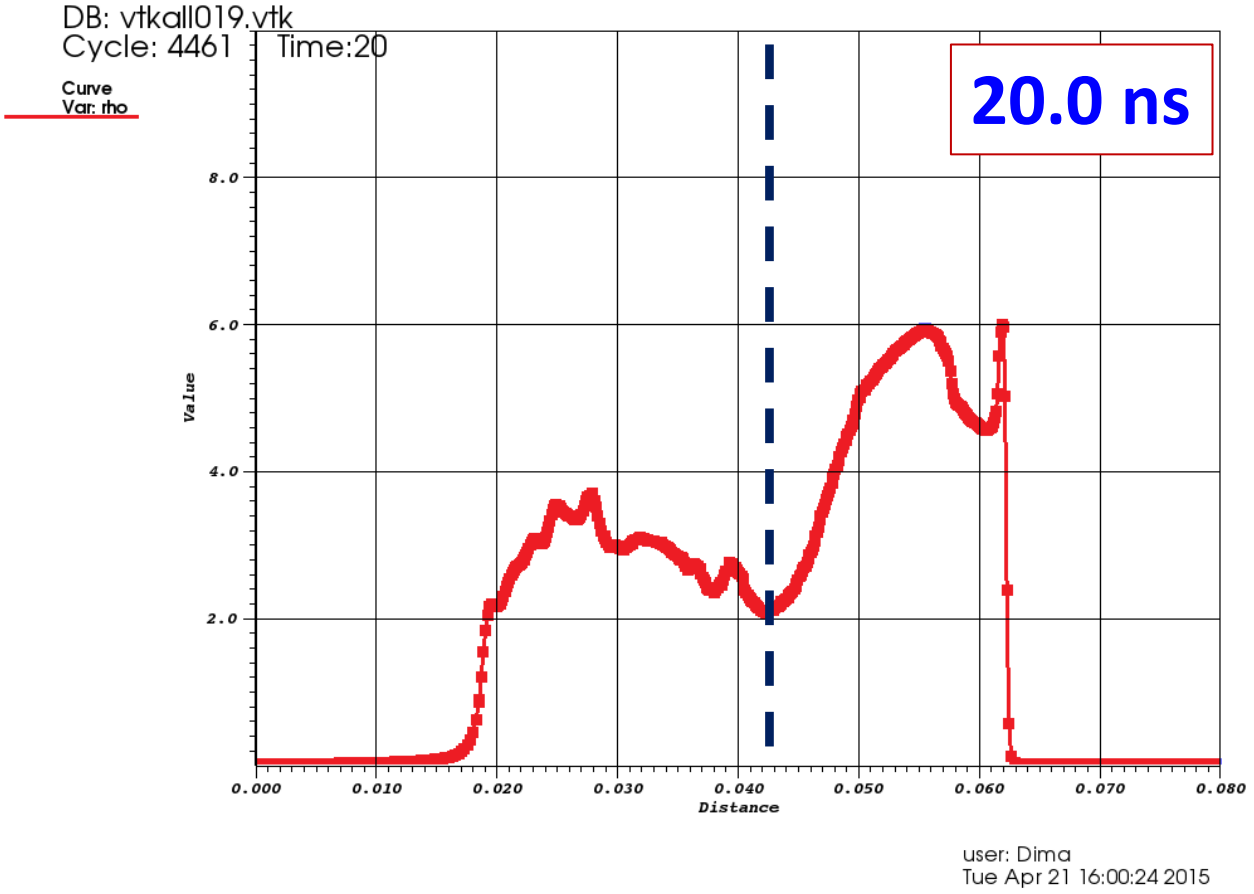




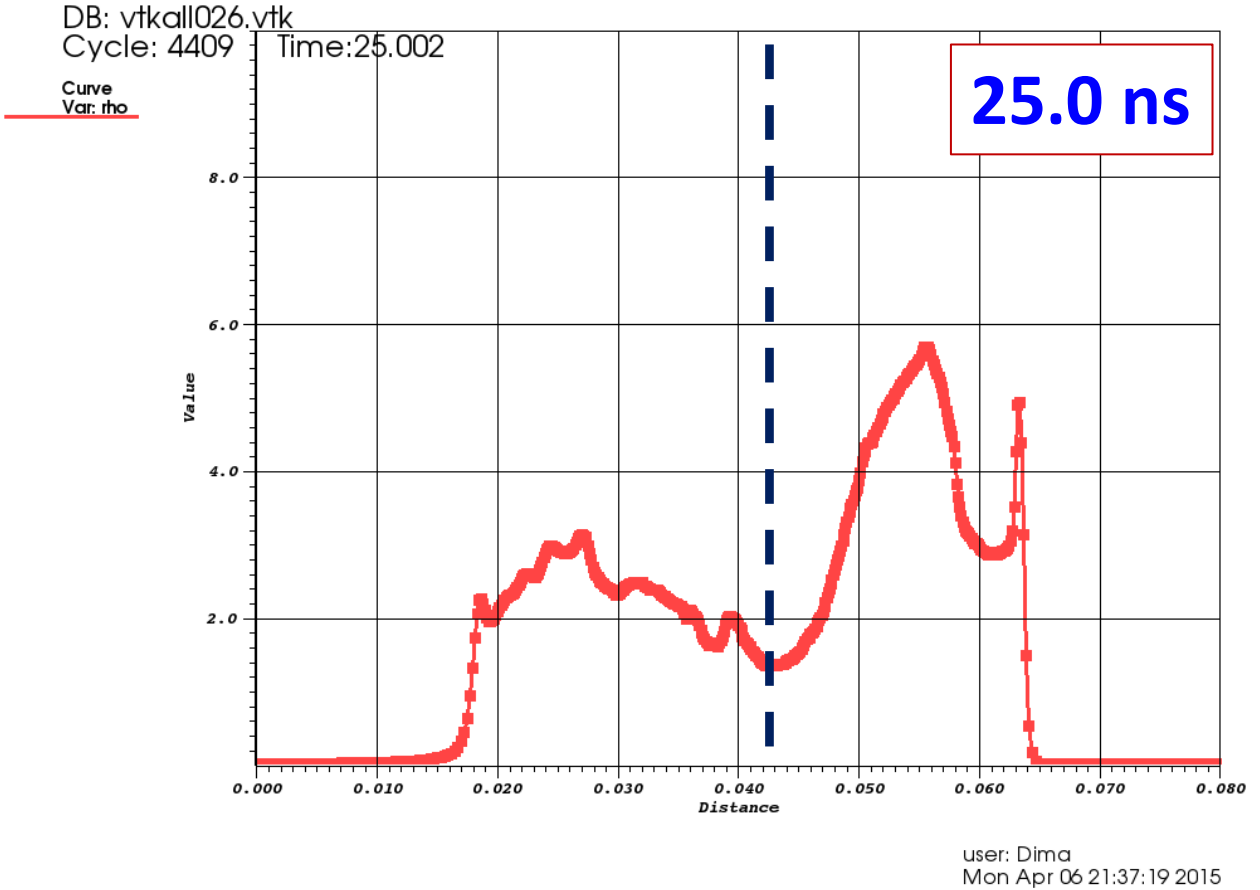
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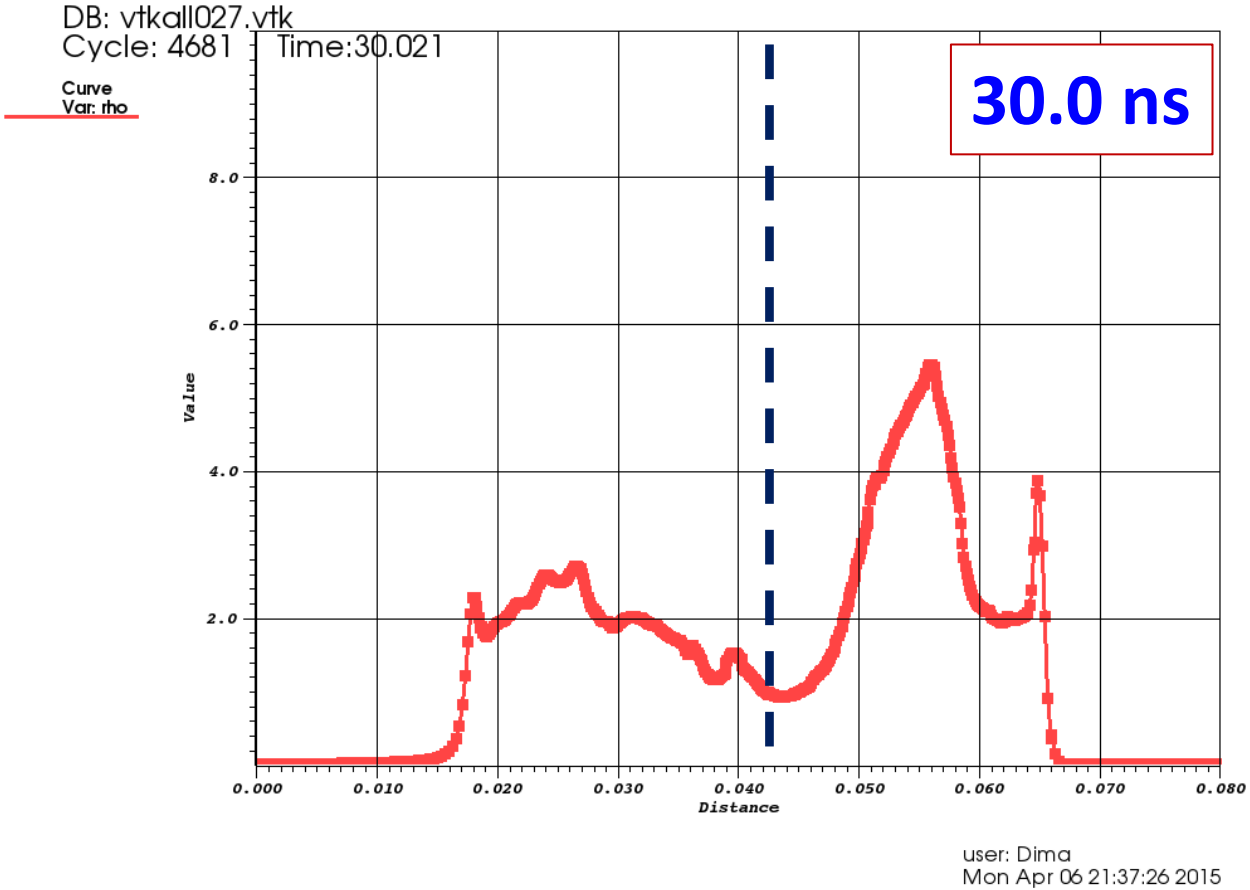
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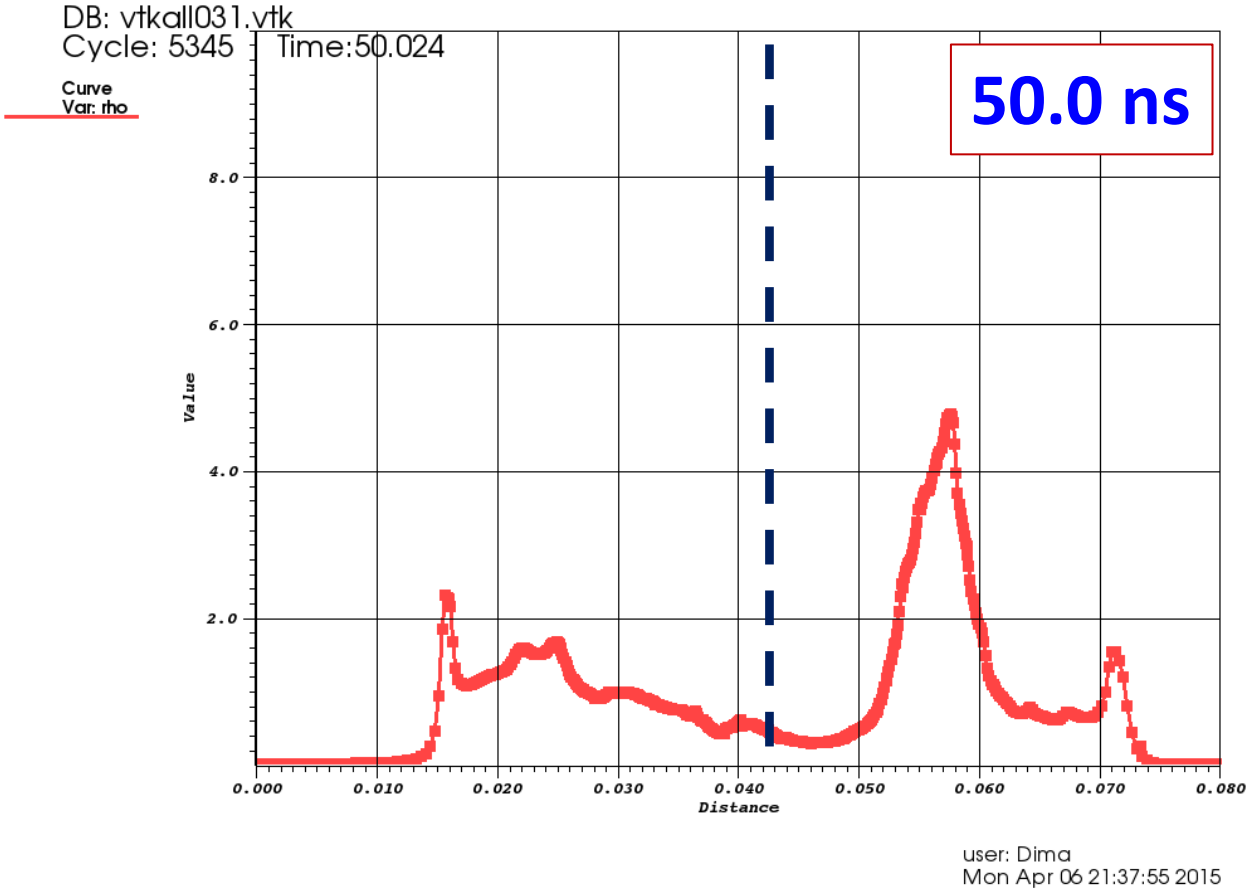
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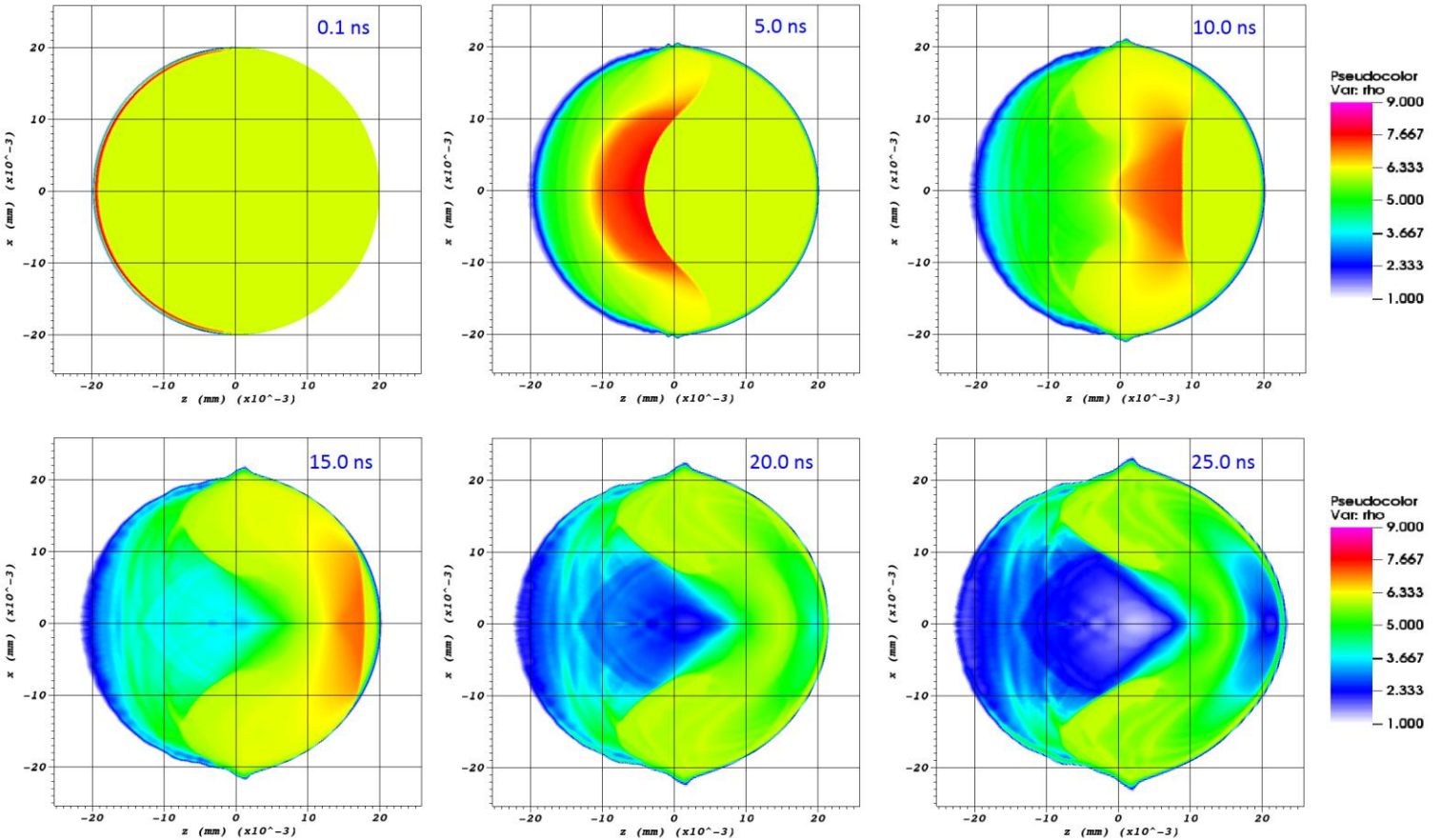
Evolution of density profile



Evolution of density profile



Evolution of tin density profile



Evolution of tin density and pressure profiles

Shock propagation within 0.5 - 10 ns time range in 1 ns steps

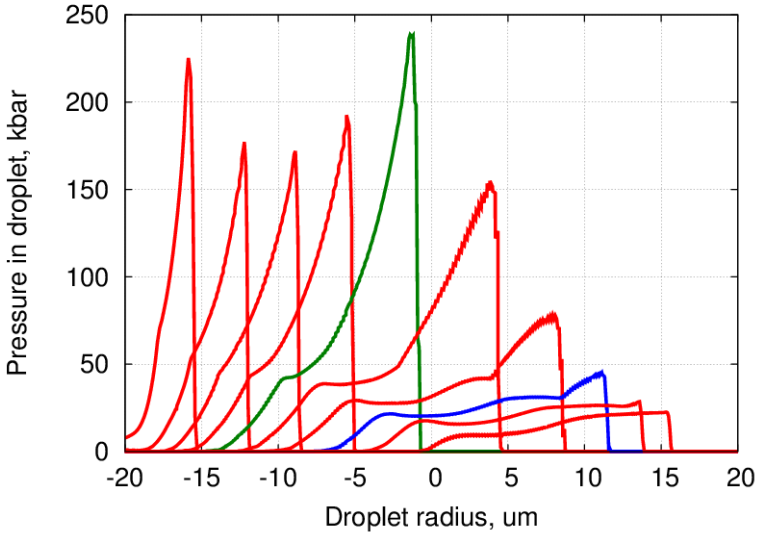


Fig.2 Shock structure: evolution of pressure in snapshots at every 1ns.

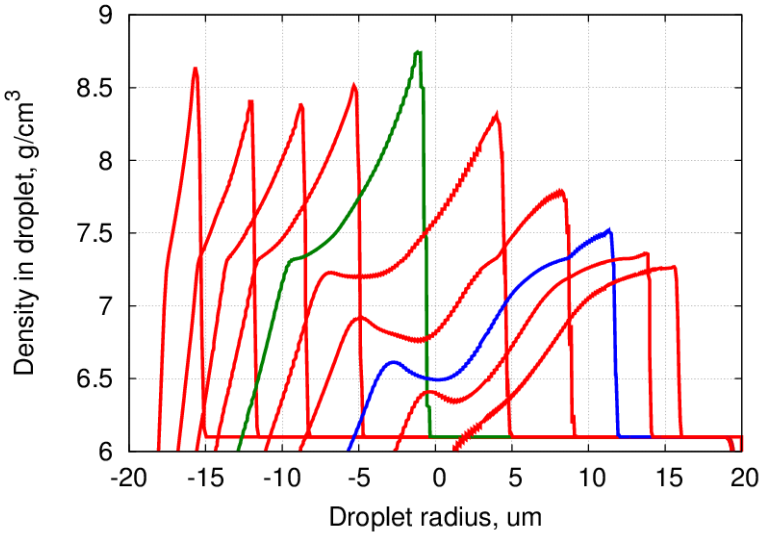
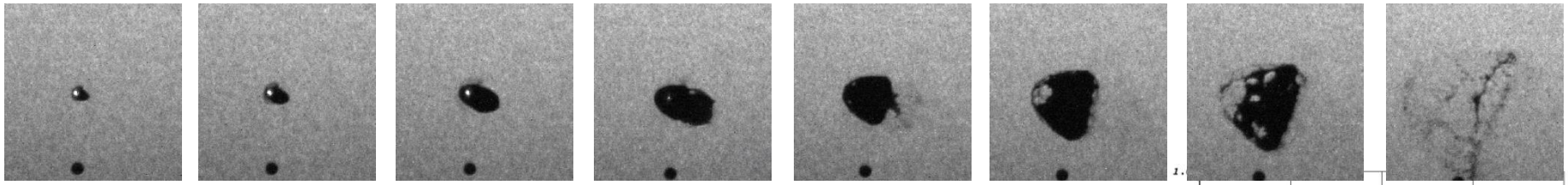


Fig.3 Shock structure: evolution of density in snapshots at every 1ns.

Evolution of tin density profile

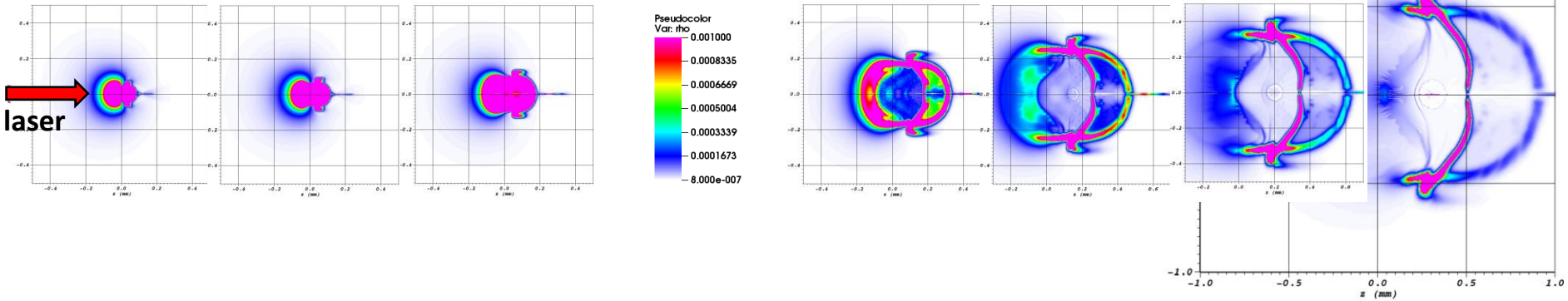
Delay after laser pulse:

0.2 us 0.3 us 0.5 us 0.7 us 1.0 us 1.5 us 2.0 us 3.0 us



1000 um

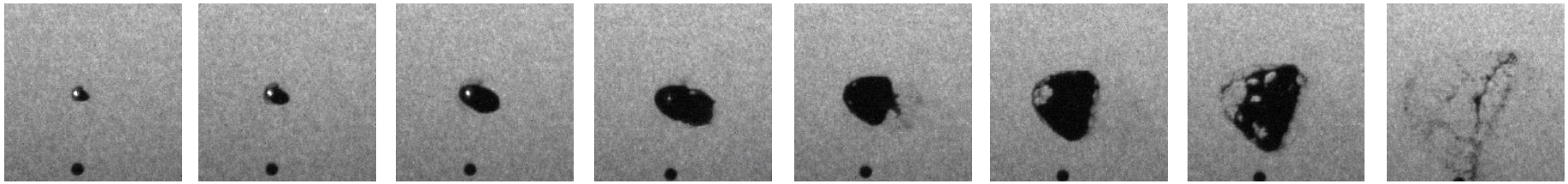
The same scale



Evolution of tin density profile

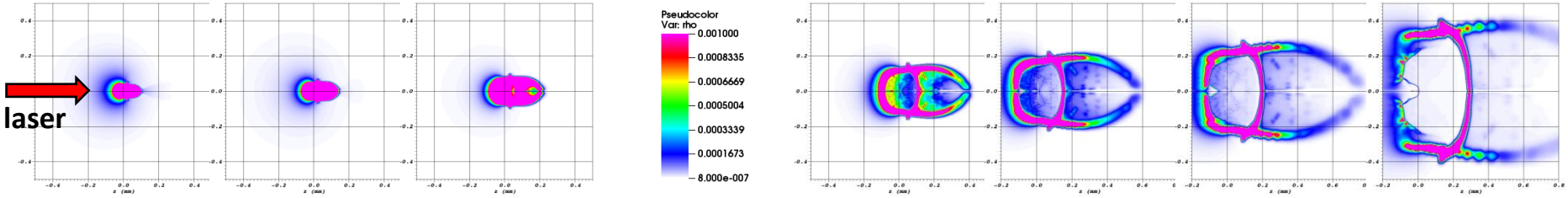
Delay after laser pulse:

0.2 us | 0.3 us | 0.5 us | 0.7 us | 1.0 us | 1.5 us | 2.0 us | 3.0 us



1000 um

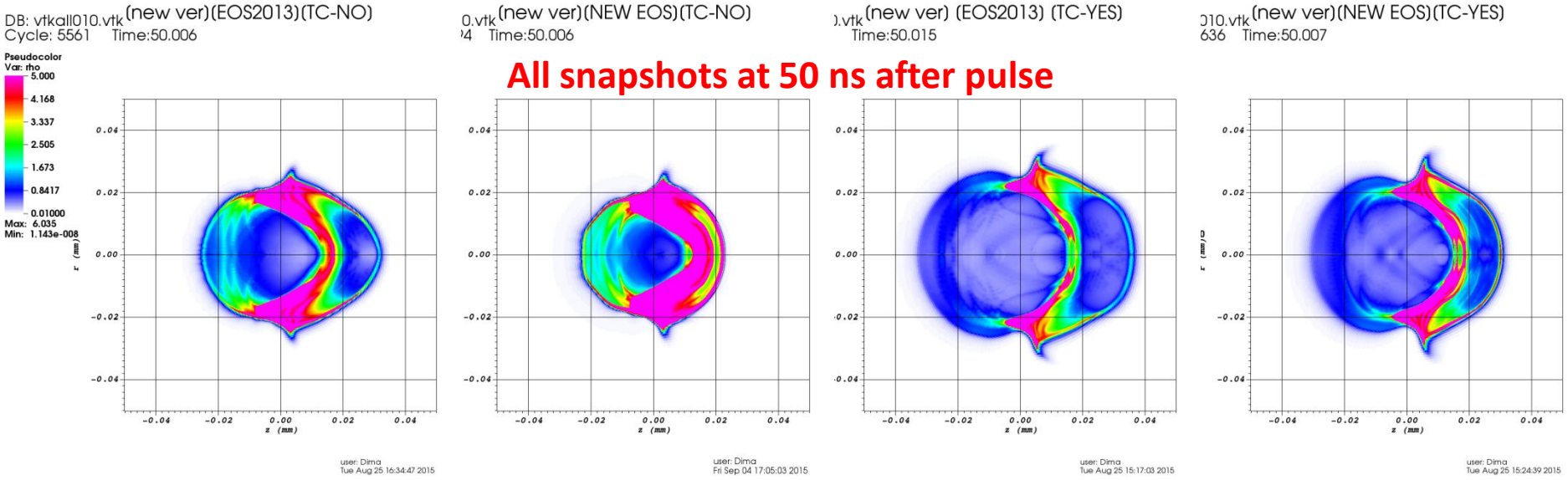
The same scale



Different model for thermal conductivity

Sensitivity to the model parameters

- Laser absorption model
- Thermal conductivity model
- Equation of state and particularly critical point (?2.8kbar or 6.5kbar)



Summary

Experiments -> stable target formation pattern resulting in ‘dome’ target over 50 fs – 5 ps pulse length range

Simulations -> 1st attempt to describe hydrodynamics of target formation using radiative hydrodynamics code (RALEF)

Laser irradiation of the droplet results in the formation of hemispherical shockwave. This shock propagates through the droplet body during tens of nanoseconds.

Shockwave propagation through the body of droplet determines the following two cavity target morphology. “Left” cavity is formed due to the shockwave focusing to droplet center. “Right” cavity is formed due to surface spalling by the shockwave reaching the free liquid surface

Thank you for your attention



Evolution of target temperature

